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TRANSLATION

AIRPLANE NAVIGATION
(SAMOLETOVOZHDENIYE)

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By V. I. Sokolov, Maj. Gen. in Aviation

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PREFACE

In the present textbook, problems in the theory and practice of aeronavigation are set forth and instructions are given on locating an aircraft in flight and guiding an aircraft from one place to another, starting with its take-off to its landing inclusive.

The science which teaches the ways and means of aeronavigation is called the theory of aeronavigation.

The complex actions of the crew of an aircraft in flight, when applying the means of aeronavigation, in order to reach the destination of flight is called the practice of aeronavigation.

It is evident from the above definitions, that theory and practice of aeronavigation are necessarily interconnected. The theory gives the knowledge - how and by what means it is possible to accomplish a flight from one place to another; the practice gives the experience - when and what to apply in order to carry out the flight successfully. In this consists the dialectical interconnection of the theory and practice of aeronavigation.

For this reason, the present textbook consists of two parts; the first covering the principles of the theory and means of aeronavigation; the second describing the practice of aeronavigation. As a whole, the book is intended to teach one of the most important disciplines of the science of aviation - aeronavigation - to the students of aviation schools and the flight personnel of fighting units of the Air Force.

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The present status of development of aeronavigation permits safely to carry out flights under various meteorological conditions, at various times of the day and at any locality.

It was shown by the experience of the Great Fatherland War and by practical flights during the postwar period, that accurate aeronavigation in any flight is impossible without a wide, and mainly, a skillful application of technological means of aeronavigation.

The various technical means at the disposal of the aircraft crew, assure an accurate completion of flight over predetermined routes, arrival at destination at rigidly set times, overcoming unexpected flight complications, and safe landing under poor visibility.

By technical means of aeronavigation are meant the ground radiotechnical and other installations as well as the airborne equipment.

Present-day technical means of aeronavigation are divided into three groups, according to the principle of action, character of use, and conditions of application.

The First Group comprises common means of aeronavigation. These are: magnetic compass, air speed indicator, altimeter, clocks and other instruments, which are installed on every aircraft, and are applicable under all conditions and at all stages of any flight. For their functioning, these instruments do not require ground support of aeronavigation or illumination from celestial bodies.

The Second Group comprises radiotechnical means and systems of aeronavigation, which include aircraft as well as ground installations, whose combined use permits solving many problems of aeronavigation under complicated flight conditions.

The Third Group includes astronomical devices: aviation sextants, astrocompasses, chronometers and others which, at various latitudes permit accurate position fixing of the aircraft and determination of the direction of flight, by observing the celestial bodies without aid from any ground means.

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In order to make various navigational calculations and measurements on maps, the crew has at its disposal navigational computing and measuring instruments: course-and-speed computer, navigational computer, drawing scales, protractor, and calculating aids (graphs, Tables). Besides that, for aeronavigation could be applied various light techniques and orientation signs, such as beacons, projectors, and also signal means (pyrotechnical), smoke generators, flares, etc.

The condition of present-day aeronavigation can be characterized by considerable speed, high altitude of flight, considerable radius of action of the aircraft, and also unavoidable changes in meteorological conditions, which complicate the work of the crew in flight.

During combat activities, the conditions of flights are often changed and need rapid decisions as to changes in course, altitude, speed, and other elements of flight. Therefore, for safe aeronavigation the flight personnel must not only learn the principles of the theory and means of aeronavigation, but must also master the indispensable knowledge of such disciplines as aviation meteorology, wartime geography, tactics, and particularly the practical aspects of aeronavigation.

A SHORT HISTORY OF THE DEVELOPMENT OF AERONAVIGATION

Pre-eminence in creating and perfecting technical means of aeronavigation, in working out ways to use those means for completion of flights under various conditions, belongs to the scientists, engineers, pilots, and aviators of our country.

Our country built the first balloon in the world, the first aircraft, and the first autogyro. It is in our country that, for the first time in the world, orientation in flight by the aid of instruments was realized. Our country can rightfully consider itself the birthplace of aeronautics, the birthplace of aeronavigation.

The sources of the scientific principles of present-day aeronavigation are contained in the works of the Russian scientists and practical workers including seamen, aeronauts, and aviators. The great labors, inventions and devices by the leaders of Russian science M.V.Lomonosov, D.I.Mendeleyev, K.E.Tsiolkovskiy, N.Ye.Zhukovskiy, academicians Ya.D.Zakharov, I.P.Kolonga, admirals of the Russian fleet G.I.Butakov, S.O.Makarov, A.N.Krylov, outstanding inventors A.F.Mozhayskiy and A.S.Popov, aviators P.N.Nesterov, Ye.N.Kruten, A.N. Zhuravchenko, and many others laid the foundations of the theory and practice of aeronavigation.

A distinctive trait of the creative power of the Russian scientists and inventors, responsible for the development of the foundations of aeronavigation, was that, from the very beginning, they did not follow the path of dry empiricism in the development of aeronavigation, but that their first practical steps in this direction were thought out and based on theory. This gave them a possibility of correctly foreseeing the path of future development of aeronavigation.

The inventor of the first aircraft in the world, A.F.Mozhayskiy, even before his aircraft took off, was already thinking of means and instruments by which to navigate it. He installed on his aircraft instruments essential for aeronavigation: clock, altimeter, air speed indicator, and magnetic compass, especially built for this purpose by academician I.P.Kolonga.

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The later developments of aviation completely confirmed the justification of A.F.Mozhayskiy's predictions. It is known that all contemporary aircraft are equipped with special navigational instruments, and that the crew of multiseat aircraft always includes a navigator, responsible for aeronavigation.

During the period when aviation first began to develop, the seamen of the Russian fleet had already great experience in ship navigation, and this experience was utilized by aviators. Yet, the aviators did not just mechanically transfer the method of naval navigation to aviation. They critically reviewed the methods of marine navigation and utilized everything that was valuable and acceptable, also respecting the experience of aeronauts, and independently worked out the problems of aeronavigation.

Various instruments and other means, specially designed for aeronavigation, were invented. At the end of the Nineteenth Century, the Russian inventor M.M.Pomortsev constructed the first navigational pelorus in the world, consisting of a combination of compass and optical sight. Similar peloruses began to appear abroad only ten years later. In Russia the first special flight map was created. There were also invented instruments for measuring ground speed of an aircraft, course and speed computers of the vectorial type, astronomical instruments, and many others.

The progress of Russian aviators in the exploitation of the theory and practice of aeronavigation was demonstrated at the beginning of World War I, in unheard-of long-distance flights of the domestic aircraft "Russian Knight" and "Ilya Muromets". In the year 1914, the flyer P.N.Nesterov accomplished the outstanding flight from Kiev to St.Peterburg. He skillfully selected a flight route of the shortest distance (air line) and completed the flight in one day, flying 1250 km in eight flying hours.

To the Russian aviation great credit is due in conquering the Arctic. The first flyer in the world to accomplish flights beyond the Arctic Circle was the Russian flyer I.I.Nagurskiy. On 8 August 1914, being a member of the rescue expedition directed to search for the polar explorer G.Ya.Sedov, the flyer Nagurskiy with the

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motorist Kuznetsov made a flight in the region of Novaya Zemlya. The flight was carried out under complicated meteorological conditions and lasted 4 hrs and 30 min.

"I was flying - reports Nagurskiy - along the borders of Novaya Zemlya by the aid of a compass... From the north appeared dense clouds, below there was heavy fog. Orientation became very difficult... I was flying in dense clouds for a full hour..."

Nagurskiy found his way by the aid of a sloop compass prepared in the workshops of the Hydrographical Bureau in Petrograd.

All together, I.I.Nagurskiy completed 10 flights, five of them long-distance.

In the years of World War I, the Russian aviator, now professor, the honorable scientific and technical worker, Stalin Prize Laureate, A.N.Zhuravchenko, serving at the time in an artillery unit of heavy airships, was the first in the world to work out and verify in practice a method of navigation of an aircraft under complicated meteorological conditions by the aid of a compass and other instruments. He also suggested the methods of measuring wind in flight when land is visible as well as above the clouds.

Those and many other works of Russian scientists, designers, and flyers are proof that Russia, where the first aircraft in the world was built and took off, was also the birthplace of the theory and practice of aeronavigation. Our native aviation ideas and flight practice were foremost already in pre-revolutionary days, notwithstanding the fact that the pioneers of the Russian air fleet had to overcome the inertness and routine of the ruling circles of Tsarist Russia, cringing before foreign countries.

With the victory of the Great October Socialist Revolution, our country established the most progressive social and political order, the creative powers of the nation were freed, unlimited perspectives for the development of all branches of science and technology were opened. During this time, the Air Fleet of the Soviet country, developed after October, was developing and gaining strength, and with its growth Soviet aeronavigation was being formed.

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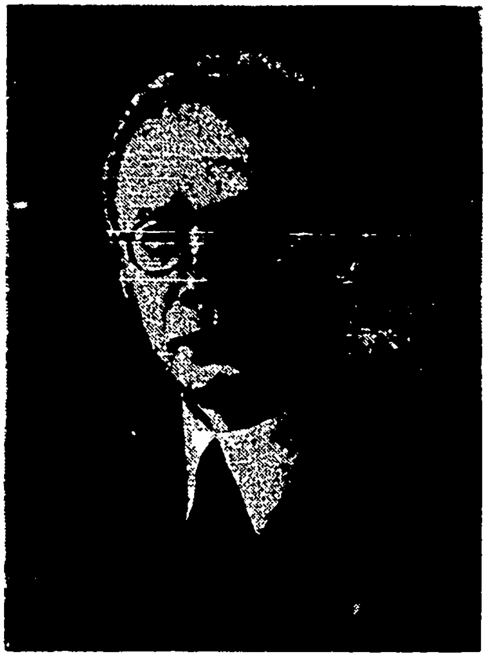
The creation and development of the Soviet Air Force is intimately connected with the work of the Communist Party and the Soviet Government.

The leaders of the Communist Party and Soviet Nation V.I.Lenin and I.V.Stalin, from the first days of the existence of the Soviet Government, took all measures to create strong Soviet armed forces, for the defense of our native land from foreign interventionists and domestic counterrevolution. The Central Committee of the Communist Party and Soviet Government made all the important decisions, embracing all sides of organizing the armed forces; this included the Soviet aviation: problems of organizing air detachments, preparing of cadres, flight application, etc.



A.N.Zhuravchenko

In the year 1919 a school for communist airmen-observers was organized. In August 1920 work had begun in the aeronavigational section of the Higher Aerophotogrammetry School. Among its first graduates were prominent aviation pilots famous in our country, the Heros of the Soviet Union, A.V.Belyakov and S.A.Danilin.

In 1921 the following schools were opened: in Petrograd, the Military Academy for Airmen-Observers; in Serpukhov, the Artillery and Bombing Academy which were later merged into one school known as the Third Orenburg School for Airmen-Observers.

At the same time great attention was paid to the creation of scientific aviation research institutes. In December 1918, the Central Aerohydrodynamic Institute (TsAGI) was established. In addition, operation was started of the Scientific-Experimental Aerodrome, an Institute of the engineers of the Red Air Force, which was reorganized in 1922 into the Air Force Engineering Academy imeni Professor

N.Ye.Zhukovskiy. In March 1923 the first scientific-testing establishment for problems of aeronavigation was opened, the Central Aeronavigational Station (TsANS), which after October 1924 became part of the Scientific-Experimental Aerodrome.

The greatest advances in scientific testing work in the field of aeronavigation began in 1925. At that time several special scientific research institutes in the field of radio engineering of special electrical equipment were established. This included the aeronavigational bureau, which consisted of the following: B.V.Sterligov, S.A.Danilin, I.T.Spirin, S.S.Tikhenev, and others. The activities of these establishments considerably influenced the laying of the foundations of Soviet aeronavigation.

B.V.Sterligov

The Soviet airmen, inspired by the constant attention of the Communist Party and Soviet Government did a lot to solve a diversity of problems in the theory and practice of aeronavigation.

In those days, the Soviet pilots faced the problem of familiarizing themselves with the methods of piloting aircraft over given routes, independently of the presence and visibility of ground marks, and with use of navigational flight control instruments: magnetic compass, altimeter, air speed indicator, clock and aircraft sight pendant.

Although the work of instilling the idea of the use of instruments for aeronavigation was complicated, the persistent and tenacious labors of Soviet navigators, airmen and engineers, led to the successful solution of this problem by the end of 1927. The problem of aeronavigation during day and night, over land and sea, was

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solved in the Soviet Aviation theoretically as well as practically.

This was followed by the problems of aeronavigation in poor visibility (in clouds and above the clouds). At the time when the flyers familiarized themselves with navigating aircraft by the aid of instruments without visible natural horizon, the navigators mastered the art of flying aircraft in the clouds. This task turned out to be even more complicated, but the persistent labor, the keen mind, and inventiveness of the Soviet people overcame that difficulty. Closed cabins for the training of airmen were developed, instructions for "blind" navigating were written, improved were the methods of calculating and laying out the flight path under conditions of zero ground visibility. The first cross-country flight in dense clouds was accomplished by the navigator S.A.Danilin in February 1928. Later many Soviet navigators mastered such flights.

S.A.Danilin

In the course of working out the problems of aeronavigation with invisibility of landmarks, the method of position fixing in flight by celestial bodies was greatly improved. Great work in this field was done by V.P.Vetchinkin, A.N.Volochov, L.P.Sergeyev, R.V.Kunitskiy whose efforts greatly enriched aviation astronomy.

At the beginning of 1929 a method of navigating a monoplane during day and night under complicated meteorological conditions was fully developed. It was necessary to try out practically in every detail all the work done in this field. Such a check was the flight during the fall of 1929 from Moscow to New York over the Far East on a Soviet twin-engine bomber TB-1, designed by A.N.Tupolev. The crew of this

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aircraft (commander S.A.Shestakov, navigator B.V.Sterligov) covered 21,242 km flying over the Siberian Tayga, the Okhotsk and Bering Seas, and the entire North American Continent. The undertaking of a group of American "Douglas" aircraft to fly the same route (in the opposite direction) failed.

In another great flight in September 1930 over the route Moscow - Ankara - Teheran - Kabul - Tashkent - Orenburg - Moscow, the group of Soviet aircraft P-5 was led by the navigator, now Hero of the Soviet Union, I.T.Spirin.

I.T.Spirin

The results of work in the development of aeronavigation were published in 1930 by B.V.Sterligov in the Handbook for Air Navigation. The book gave details on practically proven methods of aeronavigation. In 1932 the first detailed official publication on the problems of aeronavigation was published: Instructions for the Air-Navigation Service (NANS).

The next stage in the development of the Soviet aeronavigation was the mastering of the art of navigating large groups of aircraft.

In the spring of 1932, the Soviet Government, during the celebrations of May Day decided to conduct an air parade over Red Square in Moscow. The problem was how to assemble and conduct a large group of aircraft of various types and speeds in a given formation at an exactly set time over Red Square. At that time, the only means of assembling groups was assembly by flying in a circle over the airfield. In this case, this method was unsuitable, since it did not permit gathering a large number of aircraft from several airfields.

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The Soviet navigators brilliantly accomplished the given task. At the parade, the method of assembling on a loop of large aircraft groups, suggested by B.V.Sterligov, was used for the first time. Over the capital of our Motherland flew orderly columns of Soviet aircraft.

Later, the methods of assembling and navigating large groups of aircraft were used not only for air parades, but also in combat preparations of aviation units and formations. The gathered data were compiled in the book by B.V.Sterligov, published in 1934: "Navigation of Large Air Force Formations within a Limited Radius".

In 1933, in summing up the fulfillment of the first Five-Year Plan, I.V.Stalin said: "The Soviet Union has turned into a country mighty in defense, a land ready for any emergency, a land capable of producing, on a large scale, all the latest defense weapons and supply its army in case of attacks from without."

As a result of the successful fulfillment of the first Five-Year Plan many branches of industry were reorganized. "We never had an aviation industry, but we have one now" pointed out I.V.Stalin in his paper on the results of the first Five-Year Plan during the joint Plenum of the Tsk and Tskk VKP (b).

The coming years were years of unbroken growth of the strength of the air fleet of our country. The Soviet aviation industry produced first-rate aircraft, equipped with perfected instruments, guaranteeing flights of long distance under complicated weather conditions. In 1935, Soviet Aviation was equipped with new high-speed aircraft of the monoplane type, whose flying speed was increased by 30 - 40%. The aircraft were equipped with radio-engineering devices, intended for securing flight control from the ground by radio and accurate aeronavigation.

In the creation of radio-engineering equipment of contact and aeronavigation, a large group of Soviet scientists, designers and engineers did successful work: M.A.Bonch-Bruyevich, A.I.Kovalenkov, B.A.Vvedenskiy, N.A.Korbanskiy, V.V.Shirkov, and many others.

By the end of 1935, Soviet aeronavigation had achieved great success. Complicated flights were no longer the accomplishment of a few individuals, but of entire detachments and units of the Air Force. The civilian air fleet changed to regularly scheduled flights, by day and night under difficult weather conditions.

Paying special attention to the development of aviation in the country, the Communist Party and Soviet Government set the Soviet flyers the ambitious goal: "To fly farther than anyone else, faster than anyone else, and higher than anyone else". The fulfillment of this task, was excellent training for preparing highly qualified cadres of Soviet airmen and navigators. The application of new methods of aeronavigation opened new perspectives and secured long-distance flights, by day or night under complicated meteorological conditions.

In those years, the heroic flights of our aviators followed in quick succession, clearly demonstrating the maturity of Soviet aeronavigation.

On 20 July 1936, a crew consisting of the pilots V.P.Chkalov and G.F.Baydukov and navigator A.V.Belyakov completed a heroic flight over the route Moscow – Franz Josef Land – Severnaya Zemlya – Bay of Tiksi – Petropavlovsk Kamchatsky – Island of Udd. In 56 hr 20 min, the crew flew 9374 km under complicated meteorological conditions and successfully landed on the Island of Udd (now Chkalov Island).

On 18 June 1937, the same crew started a flight over route Moscow – North Pole – U.S.A. After 63 hr 16 min, the aircraft ANT-25 (TsAGI-25) safely landed on the Portland (U.S.A.) airport, having covered a distance of 9130 km, including 5900 km over oceans and ice.

In less than a month on 12 July 1937, a second crew, consisting of the pilots M.M.Gromov and A.B.Yumashev and navigator S.A.Danilin flew over the North Pole. For 62 hr 17 min, the aircraft flew on a straight line 10,200 km and safely landed in San Jacinto (California). And a new world record was established for length of flight.

Shortly before these flights, on 21 May 1937, a brilliant flight of heavy aircraft was carried out over the North Pole, under the leadership of navigator

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I.T.Spirin. In all those flights, all achievements of Soviet aeronavigation were skillfully used, including all radio means and aviation astronomy.

The year 1938 brought new victories to the Air Fleet of our country. On 27 June, pilot V.K.Kokkinakiy and navigator A.M.Bryandinskiy completed a nonstop flight from Moscow to Spassk airfield in the region of Vladivostok. The aircraft was in the air for 24 hr.36 min, covering a distance of over 7600 km over the Tayga under complicated meteorological conditions. In the same year a nonstop flight over the route Moscow - Far East was completed. The crew consisted of V.S.Grizodubov, P.D.Osipenko, and M.M.Raskov. With the aircraft "Rodina" heroic Soviet women pilots flew on a straight line 5908.61 km in 26 hr and 29 min and established a new international women's record for long-distance nonstop flights.

A.V.Belyakov

Those and many other flights of Soviet pilots graphically showed to the entire world the strength of our Air Fleet, re-armed by modern technology in the years of the first two Five-Year Plans, showing the triumph of advanced Soviet aeronavigation.

In the years of the prewar Five-Year Plans, considerable attention was paid not only to the mastering of cross-country flights under complicated meteorological conditions, but also to landing at low or zero visibility. In those years, great achievements were made in equipping aircraft with special instruments, as well as in working out of methods for utilization of these instruments.

All the important prewar experience in aeronavigation was published in the late

Thirties in manuals and instruction books, which gave the orders and rules of aeronavigation, tested by actual experience. Special mention should be made of the "Aeronavigation Manual" published in 1937.

The papers by B.V.Sterligov, N.F.Kudryavtsev, N.K.Krivonos, R.V.Kunitskiy, L.P.Sergeyev, M.F.Gorshkov, V.Yu.Polyak, V.V.Shirkov, B.G.Nemchinov, Ye.P.Titov, N.A.Nosov, B.G.Rats, and others contained solutions to all the basic problems of the theory and practice of aeronavigation. Nowhere in the world were the following problems worked on in such detail as in our country: aeronavigation under difficult conditions, assembling and navigating of large groups of aircraft of various types, deviation of magnetic compasses, use of radio-engineering means and astronomical devices for aeronavigation, accuracy of navigational measurements, and many others.

The Soviet people, under the leadership of the Communist Party, successfully fulfilled the prewar Five-Year Plans. As a result, our aviation had first-rate aircraft, equipped with perfected navigational instruments, at the beginning of the Great Fatherland War. Soviet Aviation had furnished the socialist Fatherland and Communist Party with highly qualified cadres of pilots and navigators, excellently trained theoretically and practically.

Defending the honor and independence of our Fatherland, the Soviet aviators in the years of the Great Fatherland War flew combat missions by day and by night, at various times of the year, under complicated meteorological conditions, dropping their lethal load on the fascist inhabitants.

Many navigators, familiar with advanced techniques and being masters of accurate aeronavigation excelled in the combat activities. These included the officers S.M.Romanov, S.I.Kulikov, V..Ye.Sharapa, S.F.Ushakov, M.S.Kozhemyakin, V.G.Pavlov, G.P.Evdokimov, F.S.Yalovoy, N.A.Gunbin, Ye.I.Kabanov, G.S.Demidov, and many others honored with the title of Hero of the Soviet Union.

The brave navigator V.V.Sen'ko who completed 500 combat missions deep behind the enemy lines was twice awarded the medal "Gold Star".

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The Great Fatherland War confirmed the fact that Soviet aeronavigation is the most advanced in the world. The problems of the theory and practice of aeronavigation worked out in the prewar period were further developed during the combat actions of Soviet Aviation and on the battlefields of the Great Fatherland War. From year to year the navigating skill of our aviators improved, the incidents of loss of orientation decreased, and the accuracy in approaching barely noriceable targets on the battlefield increased. The Soviet navigators were highly successful in guiding combat aircraft onto military objects deep behind the enemy lines.

Noting the mastery, the unequaled valor, heroism, and courage shown by Soviet aviators in the combats for the honor and independence of our Fatherland, the Commander-in-Chief I.V.Stalin in his order No.152 on 20 August 1944 said:

V.V.Sen'ko

"Thousands of remarkable airmen, navigators, and aerial gunners constantly increase the success of our Armed Forces and are smashing the enemy on land and in the air."

In the years of the Great Fatherland War, our aviation successfully inflicted mass blows on the enemy. In these mass attacks by large aircraft formations, the navigating service faced especially complex problems. Assembling of large formations in the air, controlling aeronavigation from the ground, organizing accurate (according to time and place) coordination of various types of aviation and ground troops, providing ZOS (flight service) for the rapidly fluctuating flight zones, organizing the shifting of air unit and formation bases - all these problems were su

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cessfully solved by our navigating service.

In solving these problems and subsequently in the further development of the theory and practice of aeronavigation, successful work was done by the following Soviet air navigators, the generals and officers: B.V.Sterligov, Ye.P.Titov, M.Kh.Gordienko, I.P.Selivanov, P.F.Vladimirov, I.I.Petukhov, L.D.Goliadze, M.N.Galimov, M.N.Morosanov, G.I.Chitayshvili, D.M.Petrenko, and others.

Soviet aeronavigation has developed under conditions of an advanced social and political order, which opened undreamed possibilities for the development of science and technology, for the creative toil of the entire nation. The constant attention of the Communist Party and Soviet Government to the problems of aviation secured speedy development of all aviation sciences, among them also aeronavigation.

The theory and practice of aeronavigation was developed in our country not by just a few individuals, but by the widest circles of Soviet people - scientists and engineers, designers and inventors, military teachers, pilots and navigators, brought up in the spirit of complete devotion to our Motherland, the Communist Party, and Soviet Government.

The development of aeronavigation always was and is carried out in unison of theory and practice. As opposed to the navigator expert (navigator) in U.S.A. aviation and in other capitalist countries, who know only the control knobs of the instruments, the Soviet navigators are highly qualified specialists, well-trained builders of the Communist society, well versed in technical and tactical problems. Many navigators and pilots in our Air Force have a higher navigational education which they received in special Soviet Military Scientific Institutes.

During the Great Fatherland War, Soviet aviation was severely tested. Its cadres grew and were reinforced. Under the leadership of the Communist Party, Soviet aviation honorably discharged its debt to the Motherland, and came out of the war, as did the entire army, stronger and hardened.

In the postwar years, Soviet aviators achieved new successes, they mastered new altitudes, distances and flying speeds. Aviation techniques, in a qualitative respect had been considerably modernized, and therefore require detailed study and considerable knowledge for their full utilization in flight. New problems are appearing in all fields of aviation sciences, including the field of aeronavigation. Some problems have been worked out in detail in the past, applicable to the technical means of that time; with the appearance of new techniques, they now require revision. This holds true in all fields of our activities. The development of aeronavigation also requires a thorough study of obsolete conditions and their replacement by new ones.

Under present-day conditions, a different solution is required of the problems of group assembly, selection of routes, methods of control, improving the means under various flight conditions, and guiding the aircraft to its targets. All of this should provide a successful approach to solving the problems of aircraft guiding by radio.

As aviation sciences and techniques have achieved new qualitative higher levels of development, the problem of working out the theory of complete utilization of all aeronavigation means, available to the crew, becomes especially important, including their use under various flight conditions.

The complexity in applying all technical means of aeronavigation is due to the character of the devices themselves, which with every year become more perfected and therefore more complicated. Many of the contemporary means of aeronavigation cannot be referred to any one category. They themselves represent a complex of various mechanism uniting, in a single unit, radiotechnical and electromechanical, optical and mechanical, magneto-mechanical and radiotechnical instruments. Thus, complete utilization of mechanisms varying in their principle of action, is decided already in designing modern aeronavigation devices.

The complex use of technical means of aeronavigation is based also on the nature of use of many means, on their usefulness for an aircraft crew in solving a given

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problem of navigation of the aircraft. For instance, after referring to the compass bearing given by the ground direction finder, the crew, in order to reach the direction finder, takes a course according to the magnetic compass. The crew determines the heading of the further flight according to the magnetic compass only when the position of the aircraft can be determined visually or by any other method. So as to take a radio bearing with the help of the airborne radio instruments, the navigator should at the same time define the angle of course of the radio station on the indicator and the direction of flight of the aircraft on the magnetic or astro compass. After finding the line of the aircraft position with the aircraft sextant on the sun, the navigator will fix the position of his aircraft by finding the second position line by the aid of another method - for example, by a radiotechnical system. After locating his position by the aid of astronomic instruments, the navigator finds the altitude of flight on the barometric altimeter and the speed, on the air speed indicator.

In this way, the crew of an aircraft, after mastering the art of aeronavigation, is making use of the various complex technical means, because only then will it be able to fulfill the navigational requirements and complete a flight along a given route.

Finally, applying all technical aeronavigation means, the crew should skillfully choose the proper device or devices, depending on the condition of flight, the mission, and the set navigational circumstances.

The historical decisions of the Nineteenth Congress of the Communist Party of the Soviet Union opened wide perspectives to Soviet aviators for further development of aviation science and technology, including aeronavigation. This obligates the Soviet aviator to give all his strength and knowledge to the task of improving the fighting capacity of our Air Force, to have it always ready to rebuff any aggressor.

CHAPTER IV

RADIOTECHNICAL MEANS OF AIRCRAFT GUIDING

Of all means of airplane guiding, radiotechnical means play an especially important role. Based on the general means of airplane guiding, as indispensable for any flight, radiotechnical means permit airplane guiding under complicated meteorological conditions, both day and night.

Radiotechnical means of airplane guiding include radio beacons, airplane and ground direction finders, circular (range finders), and hyperbolic radio navigational systems.

The principal operation of modern radio technical means of air guiding is based on the properties of directional radiation, or directional reception of electromagnetic energy, or on radiotechnical methods of measuring distances.

1. Physical Bases of the Operation of Radiotechnical Aircraft Guiding

Electromagnetic energy, emitted by any wireless transmission arrangement, radiates in space in the form of oscillations or, as it is otherwise called, radio waves. Radio waves propagate rectilinearly, with a speed of nearly 300,000 km/sec. In the property of radio waves to propagate rectilinearly and with constant speed lies the basic function of all radiotechnical means of airplane guiding. However, there are certain peculiarities in the character of propagating radio waves, which depend on the length of the waves themselves.

At present, all radio wavelengths are separated into several bands, and it has

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been found that, within each separate band, the character of the radiation of radio waves is identical. The Table below lists the bands of radio waves.

Radio Wave Band	Wavelength, in m	Frequency, in kc
Long waves	10 000 - 1000	30 - 300
Medium waves	1000 - 100	300 - 3000
Short waves	100 - 10	3000 - 30 000
Ultrashort waves (Meter, Decimeter, Centimeter)	from 10 m to 1 mm	30 000 - 300 000 000

The features of the radiation of radio waves of different bands are the following:

Long waves radiate along the earth's surface, bending around it through arcs of Great Circles between radio transmitting and radio receiving stations. The extensive absorption of electromagnetic energy by the earth requires powerful radio transmitters, so as to guarantee a large operating range for the long waves. The advantages of long waves are: their propagation over comparatively large distances (which is especially important for the purposes of airplane guiding) and the negligible influence on the path of this propagation by various kinds of obstacles (mountains, rivers, etc.) and changes in meteorological factors, depending on the range of the cause and especially on the time of day and year.

Medium waves radiate along the earth's surface over small distances. However, they possess the characteristic that almost without loss they are reflected from the top layers of the atmosphere and return to the earth's surface at considerable distances from the radio transmitter. This makes it possible to realize a greater range of operation, using less powerful radio transmitters.

Just like the long waves, the medium radio waves are subject to considerable

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radio interference.

The ultrashort waves propagate in a straight line. They are not able to bend around the earth, as are the long waves, and they are not reflected from the upper layers of the atmosphere as are the medium waves, but escape into space. However within the limits of a straight line, they possess high stability in the direction of emission and readily overcome various kinds of obstacles.

A series of radiotechnical means of airplane guiding is based solely on the nature of radiation of radio waves by an orthodrome. By these means, radio beacons as well as, ground and air radio direction finding stations operate.

Other means besides this, such as ground and airborne radar sets, circular and hyperbolic systems use these properties of radio waves and the property of their constant rate of propagation.

Radio beacons and ground and air radio direction finders constitute groups of a so-called goniometer system. The principle of their operation is based on the direction of transmission or the direction of reception of electromagnetic energy.

Radio stations with directional transmission are called radio beacons.

Ordinary radio stations - broadcasting stations, airfield towers, etc. - radiate electromagnetic energy equally in all directions. Radio beacons emit radiation in rigidly predetermined directions.

In receiving radio beacon signals, it is possible to use the character of these signals for estimating the reciprocal spacing of receiver and radio beacon, i.e., to use the latter as a means of orientation. The work of a radio beacon can be compared to the work of a projector, sending beams in specified directions.

The directional radiation of radio beacons warrants special forms of transmitter antennas. Antennas of ordinary radio stations consist of horizontal wire, suspended at a certain height above the ground, or of vertical masts (Fig.97). Such antennas are known as antennas of the open type. Radiation of electromagnetic energy through these antennas is propagated equally in all directions. The strength of reception depends solely on the distance between the radio station and the receiver.

It is possible to depict this by a graphical diagram. Let the strength of reception be represented by long vectors, and the direction between the radio station and the receiver by an angle formed by these vectors and some elementary straight line OB. Then the diagram of the open antennas are represented by a circle, in

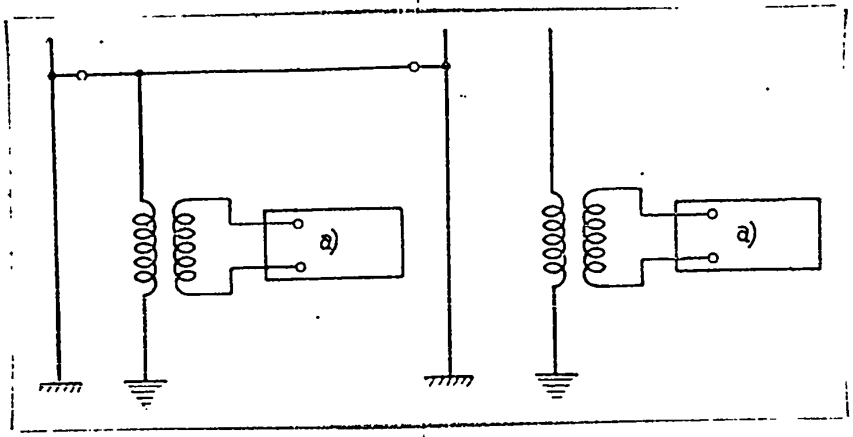

Fig.97 - Horizontal and Vertical Antennas

a) Transmitter

whose center radio stations are located, while the circle itself represents the geometric locations of points at the ends of the vectors, which give the strength of reception at the various points. Since this strength does not depend on direction, the diagram of an open antenna is represented by a circle (Fig.98).

The matter would be different if the radio station transmitted electromagnetic energy across a special form of antenna, the closed type or loop antenna (Fig.99). If the receiver near this antenna is replaced by one remote from it (in circles) and if the strength of the signal is measured, it will be found that this force depends on the direction between the transmitter and the receiver. In the direction of the plane of the antenna the signal strength will be greatest; it will decrease on farther removal from the direction of the plane, and will become equal to zero and in the direction perpendicular to the plane. The change in the strength of

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reception is graphically depicted in eight views by the diagram (Fig.100). These diagrams indicate the change in the magnitude of the vector of the reception

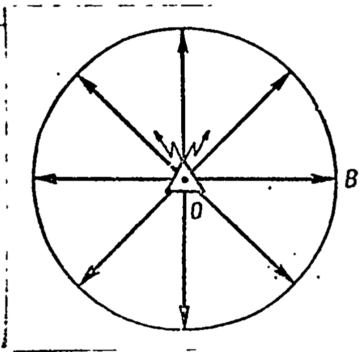

Fig.98 - Diagram Depicting an Open or Omnidirectional Antenna

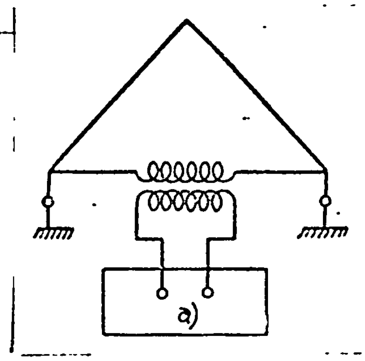

Fig.99 - Closed or Loop Antenna

a) Receiver

strength, as a function of the angle between the plane of the antenna AA and the direction of the receivers ABC. For example, at point B the strength of reception is one half the strength and at point C it becomes one fourth. At point D, at the perpendicular to the plane of the antenna, the strength of reception is zero. This directional property of the closed antenna is used in the radio beacon.

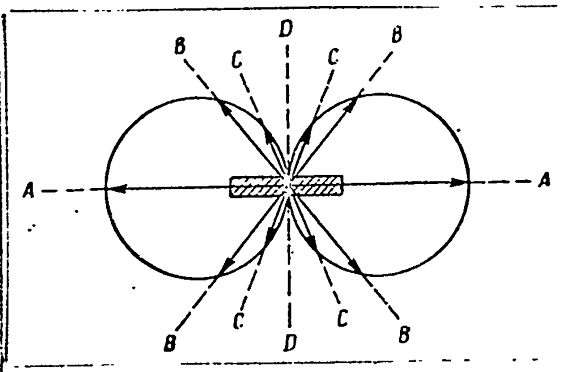

Fig.100 - Diagram Depicting Closed Antennas

Actually, if the signal strength depends on the direction, then it is possible to determine the direction to the radio station and thus use these data for the purposes of airplane guiding.

However, a single-loop antenna by itself permits only a rough determination of the direction; therefore, the radio beacons use a system of two or several loop antennas.

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<u>Airborne radio direction finders</u> (automatic compasses) are used for determining, in the airplane, the course angle of the transmitting radio stations and for piloting airplanes on a continuous angle of course relative to the given radio station.

The principle of operation of airborne radio direction finders is based on the ratio of the direction of the receiver to the loop antenna. The loop antenna (or, simply, the loop) is described as a conductor, folded on a self-induction coil of circular or rectangular form (Fig.101). If the ends of the loops are coupled to a ("antenna - ground") receiver and then tuned to the radio station, it will be found that the strength of reception depends on the angle, constituting the plane of the loop in the direction to the radio station. The strength of reception is at a maximum when the plane of the loop coincides with the direction to the radio station and is at a minimum or completely absent when the plane of the loop is perpendicular to this direction.

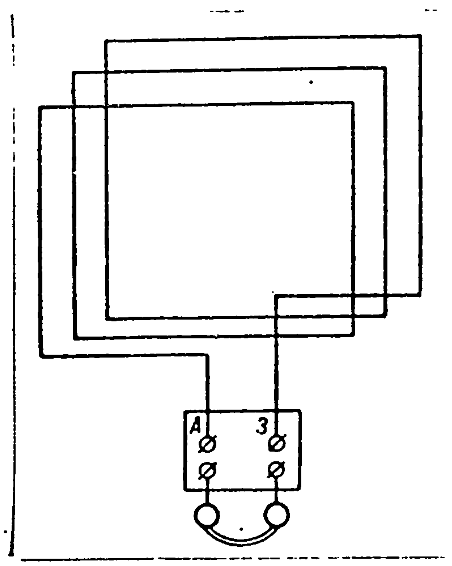

Fig.101 - Loop Antenna

The dependence of the strength of reception on the angle of the turning loop is depicted graphically by the vector diagram, analogous to the diagram depicting the closed antenna (see Fig.100). Thus, when a radio station is located at point A (in the plane of the loop) the strength of reception is at a maximum; at point B the strength of reception is two times less, etc. finally becoming zero at point D, located on the perpendicular to the loop.

Thus by obtaining the minimum strength of reception of signals from a rotating loop, it is possible to tell that the radio station, to which the receiver is tuned, is located in a direction perpendicular to the plane of the loop.

If an arrangement is set up, permitting the reckoning of the angle between any determined direction, for example, between the longitudinal axis of an airplane and the perpendicular to the loop, then this itself will permit the determination of the course angle to the radio station. However, such an arrangement does not make it possible to determine the direction in which the radio station is located. In order to avoid confusion in determining the direction, the receiver is supplemented with an open antenna of the vertical type, whose diagram of reception strength is depicted by a circle (see Fig.98) and permits simultaneous reception on both antennas (Fig.102).

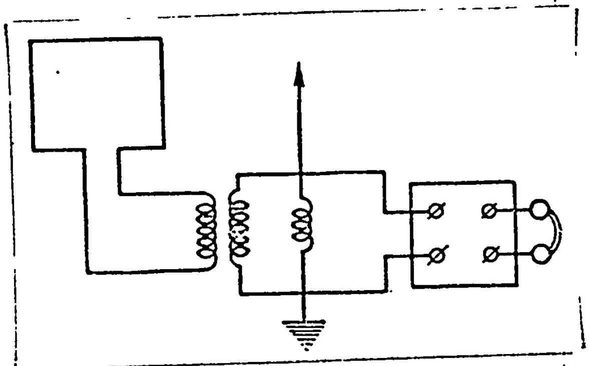

Fig.102 - Simultaneous Reception with a Loop and Vertical Antenna

At a proper selection of antenna parameters, a summary diagram of the strength of reception is given by the so-called "cardioid" (Fig.103) which simply determines the direction to the radio station, since a minimum signal (theoretically none) is located in the direction OF. However the minimum, determined by the cardioid is insufficiently precise. The minimum signal (zero) will be found not only on the line OF, but also in certain sectors of KOL; therefore, the direction to the radio station cannot be precisely defined.

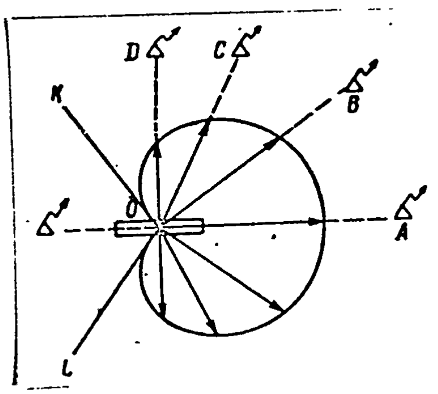

Fig.103 - Cardioid Pattern

For a precise determination of direction and location and also in order that the determination be derived not audibly but visually, the radio compass does not use a comparison of the strength of audible signals but a comparison of the magnitude of electromotive force in the loop and open antennas. This is produced with the help of individual arrangements (commutator and switch) in-

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troduced into the radio compass pickup.

In this arrangement, signals strike the visual indicator, which thus indicates the course angle of the radio compass.

The signals, showing the course angle on the indicator, are proportional to the magnitude and direction of the electromotive force (emf) whose magnitude is deter-

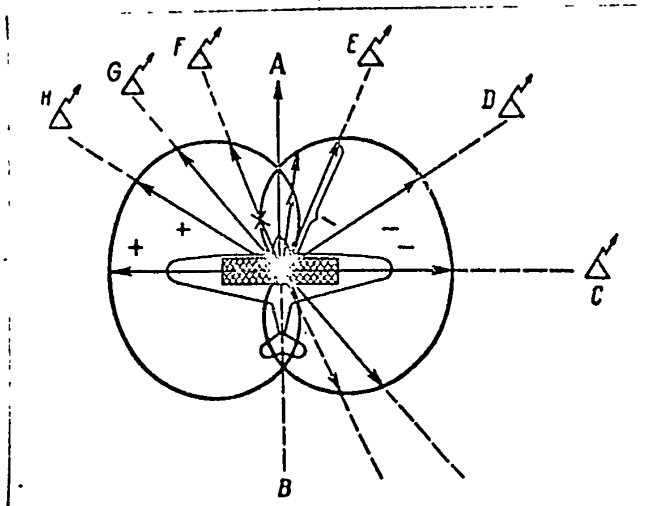

Fig.104 – Diagram of the Electromotive Force Showing the Course Angle on the Indicator

mined by a double cardioid (Fig.104). One of the cardioids is positive and the other negative. If this magnitude equals zero, i.e., if there are two emf equal in magnitude and opposite in sign, denoting the location when the radio station is situated on the line AB perpendicular to the plane of the loop, then the pointer indicating the course angle will give the course angle of the radio station.

The principle of action of ground radio direction finders is based either on the directional property of the loop antenna or on the directional property of a combination of two or four vertical antenna, so that the antenna array of ground direction finders is either a loop (similar to a radiocompass loop)or four vertical antennas.

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Radio direction finders show greatest amplification with antenna arrays of the second type, since such an antenna has a greater range than an antenna of the loop type; it is free of errors ascribed to the loop type and possesses greater coverage and greater sensitivity.

For reception with an antenna array consisting of two vertical antennas, the

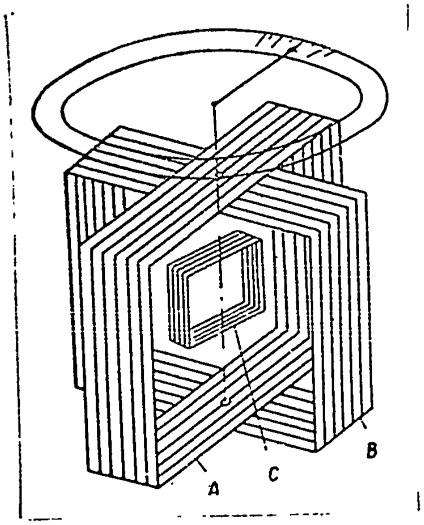

Fig.105 - Schematic Diagram of a Goniometer-Type Direction Finder

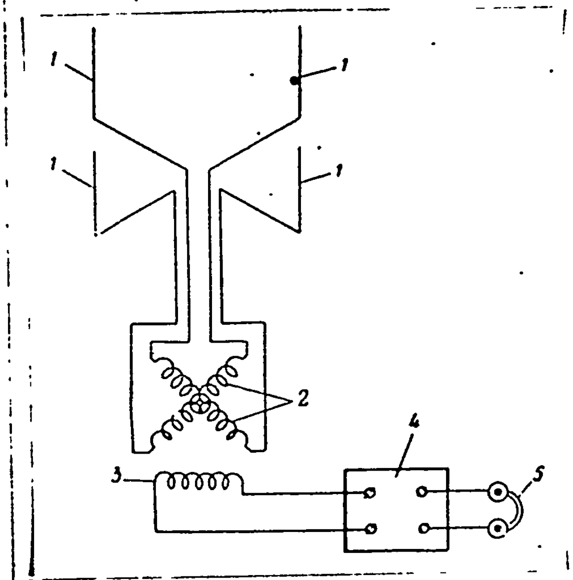

Fig.106 - Schematic Diagram of a Direction Finder

system is so adjusted that it possesses the directional properties of a loop antenna and that the radiation pattern has eight lobes, i.e., the maximum signal strength will be obtained when the direction to the radio transmitter coincides with the plane of the antenna and the minimum (nearly zero) will be obtained when this direction is perpendicular to the plane of the antenna. The erection of such a mobile system is complicated and is therefore usually replaced by two pairs of stationary vertical antennas (the planes of these pairs are mutually perpendicular) and the direction is determined with the aid of a special device known as a goniometer.

The goniometer is a system of windings, two stationary (A and B) and one moving (C) (Fig.105). The planes of the stationary windings are at right angles to

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each other and form the goniometer stator while the moving windings are inside these and form the rotor or goniometer searcher. Each winding of the stator (2) is joined to the pair of vertical antennas (1), while the searcher (3) is joined to the receiver (4) (Fig.106).

In reception with such an array, it is found that the minimum audible signal in the telephone (5) will occur when the plane of the loop searcher is perpendicular to

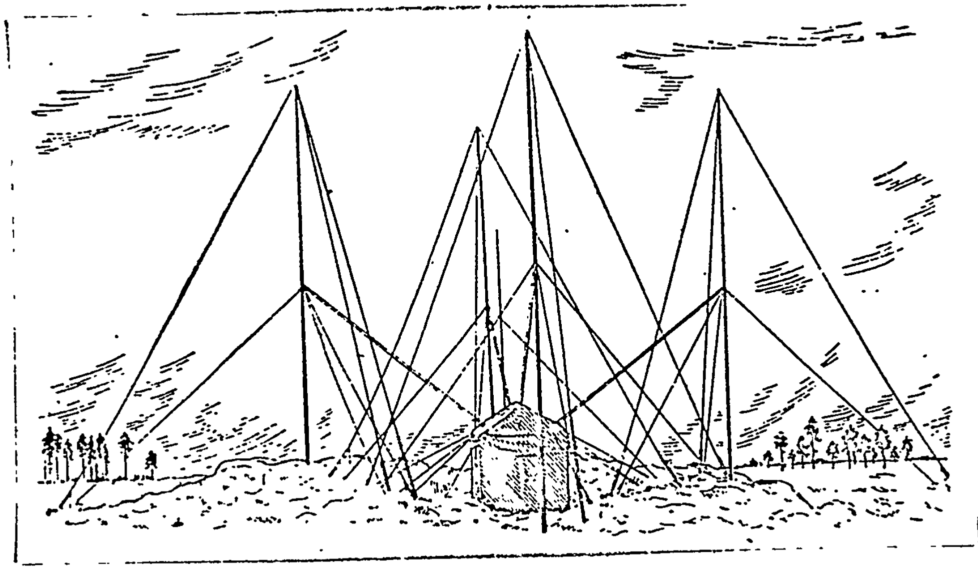

Fig.107 - Ground Radio Direction Finder

the direction of the transmitter, i.e., it is determined by complete correspondence between the goniometer searcher and the rotatable loop antenna; consequently, with its assistance it is possible to determine the direction of the transmitter.

Thus, all necessity for a rotating antenna system is eliminated; the system is replaced by a small rotating coil - the searcher. The goniometer has a scale divided into 360°; since it is known that zero on this scale corresponds to North, rotation of the searcher determines the bearing of the transmitter.

Figure 107 gives an overall external view of one of these types of ground radio direction finders. Ground radio direction finders are used for determining, from the ground, the bearing of flying airplanes.

The principle of operation of all radar and related systems is based on a determination of the distance from the radar station to the airplane. In order to explain this better, we will examine its application to the radio altimeter.

The method of measuring the altitude of a flying airplane, based on a method of barometric leveling, leads to a series of discrepancies which, if not calculated, will result in significant errors in determining altitude.

Because of this, attempts were made for a long time to design an altimeter on some other principle. In particular, altimeters were developed based on the principle of echo sounding.

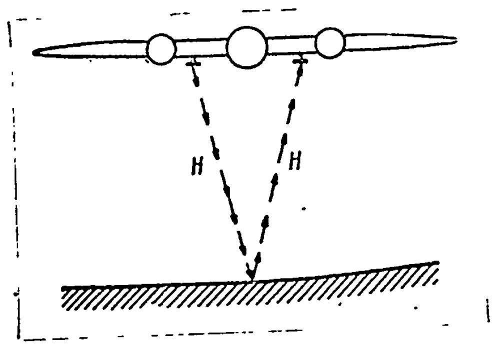

Fig.108 - Schematic Diagram of Measuring the Altitude of Flight

In echo sounding, strong sound signals are emitted which strike the earth's surface, are reflected from there, and return back to the airplane. In the air plane the interval of time between the instant of sending the original signal and the instant of the arrival of the echo was measured. Knowing the rate of diffusion of sound and indicating the interval of time, made it possible to determine the duration of the signal. It is obvious that this duration is equal to twice the altitude of the flying airplane (Fig.108).

$$H = \frac{at}{2},$$

where H is the altitude of the aircraft;

a is the rate of diffusion of sound;

t is the time interval.

However, there were also errors in measuring altitude by echo sounding. These errors were due to the inconstant rate of diffusion of sound, caused by differing reverberation from the earth's crust and caused by engine noise. Considerably better

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results were obtained by using radio signals instead of sound signals, since the practical rate of diffusion of radio waves is constant and does not depend on the medium in which they propagate.

A basic difficulty in designing a radio altimeter is the measuring of the time interval between the instant of sending the original signal and the instant of arrival of the echo. Actually the rate of diffusion of radio waves is very great and equal to

$$C = 300\,000 \ km/sec,$$

and the interval of time measurement is exceedingly small. For example, for measuring an altitude of 5 km, it is necessary to measure the time interval which equals (derived from the formula)

$$H = \frac{Ct}{2},$$

$$t = \frac{2H}{C} = \frac{2 \cdot 5}{300\,000} = 0{,}000033 \ sec,$$

i.e., the time interval equals 33 millionth of a second or, as it is expressed, 33 μ sec. For lower altitudes, the time interval will be even less. Thus, for an altitude of 150 m (0.15 km) the time interval equals

$$t = \frac{2H}{C} = \frac{2 \cdot 0{,}15}{300\,000} = 0{,}000001 \ sec = 1 \ \mu \ sec.$$

Of course, measurement of such small intervals of time is not possible and therefore an indirect method, based on achievements in radio technics is resorted to.

At present, two methods are used: the frequency method and the pulse method.

The radio altimeter based on the frequency method, works as follows: In the airplane, at a small distance from each other, a transmitter and a receiver are installed. The transmitter continually emits radio waves of constant power. However, the frequency of the transmitter, in contrast to a conventional transmitter, is not

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constant but rapidly varies in the interval between the highest and the lowest value. The receiver, at each instant, receives two signals. One signal goes immediately through a cable from the transmitter to the receiver, while the other signal is reflected and travels from the transmitter to the earth and from the earth to the transmitter. Obviously, the frequency of each received signal varies, and the difference in frequency depends on the interval between receiving the original signal and the reflected one, i.e., on the altitude of flight. Thus, measuring the difference of frequency of the received and the reflected signal will yield the altitude of flight, which is especially indicated by an altitude signal indicator. Measuring the difference in the frequencies can be done with such high accuracy, that the altitude can be measured with the accuracy necessary for flying aircraft by instrument, i.e., with an accuracy of 2 - 3 m. Frequently, the altimeter cannot measure extreme altitudes, since this demands adequate power of the reflecting signal. In general, they are used to measure altitudes from 1000 - 1500 m.

Measuring higher altitudes requires a higher power of the altimeter pickup, which necessitates a significant increase in its weight and overall dimensions. Therefore, the other method for measuring altitude, namely the pulse method, is preferably used. In this method, the transmitter sends out pulses of constant frequency. The pulses are sent at short intervals. In the pauses between transmitting the pulses, energy accumulates in the transmitter which is all transmitted with the pulse.

Thus, the energy of the pulses exceeds many times the average power of the transmitter. Measuring altitude in this case proceeds from the measurement of the lag of arrival of the echo pulses from the earth in comparison with arrival in the receiver of the original pulse. A cathode-ray tube serves as an indicator, whose screen shows the direct and the reflected signals. The distance between these signals is the measure of the altitude.

The accuracy of the pulse altimeter, although of lower frequency, significantly

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exceeds the accuracy of the barometric method.

The radio altimeter is convenient since it permits, without calculation and without supplementary operations, an immediate determination, with satisfactory accuracy, of the true altitude of an airplane. Besides this, the pulse radio altimeter permits judging the relief of the terrain underneath the aircraft; this is important in flights over unknown areas. With the aid of a radio altimeter it is possible also to determine if an airplane is flying over dry land, over the sea, or over mountains.

Analogous to the radio altimeters are the ground and airborne radar units working at great heights.

Ground radar stations are pulse transceivers and serve to discover airplanes while in flight and to determine their bearing and the distance to them. The principle of operation of a radar station is analogous to the principle of operation of a pulse radio altimeter.

By special antenna, powerful pulses of electromagnetic energy, accumulated in the transmitter over the periods of cessation of transmission, are periodically radiated. These pulses, upon encountering any object in their path, are reflected therefrom. The reflected pulses are received by the receiving station, in which, with the aid of special equipment the interval between sending the original pulse and receiving the echo is measured.

Knowing this time interval and the rate of diffusion of electromagnetic energy, it is possible to determine through the assistance of the indicator (cathode-ray tube) the distance between the station and the object. The antenna for transmitting the pulses is of a special form, depending on transmissions in carefully selected directions, by which it is possible to discover objects and determine their distance. Rotating the antenna in a horizontal plane makes it possible to conduct these determinations in any directions; the angle of turn of the operating directional antenna, relative to the Meridian of its erection site, permits determining the size

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and bearing of the objects.

Thus, it is possible to determine the distance and bearing of objects, particularly airplanes.

Due to technical reasons, radar stations operate on ultrashort waves, which can discover airplanes beyond the visible horizon of the station site.

The maximum distance between the radar station and the airplanes, across which it is possible to detect an aircraft, is determined by the formula

$$D = 3{,}57\sqrt{H_1} + \sqrt{H_2},$$

where H_1 is the height of the antenna above the ground;

H_2 is the altitude of the aircraft. The dimension D is measured in km and H_1 and H_2 are measured in meters.

The practical magnitude of D is less and depends on the parameter of the radar station. The pulse method of transmitting is used because of the small consumption of power necessary to transmit an impulse of a sufficiently high power, necessary for an adequate force in the echoing pulse.

For example, due to the consumption of power of 200 w in the pulse it is possible to have transmitted 100 kw. This also means that the radar station has a smaller range and weight than the usual radio station of continuous operation, using continuous power equal to the power of the pulse.

Ground radar stations permit detection of flying airplanes at considerable distances from its location; for example, according to the derivation of the above formula, at H_1 = 10 m and H_2 = 1000 m, this distance equals 124 km; at an altitude of flight of 4000 m the distance equals 237 km, etc. This distance is the calculated distance; practically this value will be somewhat less. Discovery and determination of the coordinates of the airplane does not depend on the weather conditions and the time of day and can function at any visibility conditions.

Ground radar can be used for navigational purpose, inasmuch as it permits

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position-fixing of the airplane.

The basic function of such stations is the detection of airplanes for sending interceptors aloft. For this purpose, the radar station (a group of radar stations) is mounted in an area protected from objects. The radar station conducts observation of the air, i.e., by the indicator of the rotating antenna, it searches within the limits of the angle of the guarded sector. The appearance of echo pulses on the indicator means the presence of airplanes in the air. In the course of several minutes the angle of travel and rate of travel of these aircraft is determined on a chart and the course and speed the destroyers must fly for interception of the enemy aircraft is calculated. This course is communicated by radio to the fighters, after which the movement of these enemy aircraft is traced, making (if needed) corrections in the course of the enemy. The purpose of the radar station is to help our destroyers in locating enemy aircraft.

The air radar station, which is mounted on interceptor fighters is the same type as the ground radar station, except that it is less heavy and serves for keeping close watch on the enemy aircraft by the fighters. Airborne radar stations are required since the insufficient accuracy of ground radar does not permit the guiding of fighters in the target area during bad weather or at night, at distances from which it would be possible to detect the target visually.

It follows that the above-described system does not guarantee sufficient accuracy in determining the direction between transmitting and receiving stations. At the same time, the pulse method guarantees very high accuracy in determining distance. In view of this, the so-called circular radiotechnical system of airplane guiding was developed. Such a system permits highly accurate determination of the distance to airplanes from two special ground radio stations, i.e., exactly as in determining the position of the airplane. The basic function of this system is its use in bombing ground targets without ground visibility, although it can also be used for solving airplane guiding problems. The limit of application of the system for airplane guiding is given by its limited range of operation since it works on ultrashort waves which, as is known, are radiated into space in a straight line.

Hyperbolic radiotechnical systems of airplane guiding also work accurately on the pulse method and are used to determine from the airplane the difference in distance between the airplane and two special ground radio stations. If all the points on the earth's surface, where the difference of the distance to the radio station is a constant quantity, are connected, a hyperbola is formed, representing the lines of position of the airplane.

Determining the difference of the distances to two other radio stations produces a second line of position which, in intersection with the first, gives the position of the aircraft.

The accuracy of determining the position of the aircraft through the use of the hyperbolic system is significantly less than that of determining it by the circular system, but the operating range is significantly greater, since the former system operates on waves which are diffused beyond the limits of visibility. Because of this, hyperbolic systems are used exclusively for solving problems of airplane guiding and as a basis for determining the location of airplanes.

The pulse (radar) system includes the airborne panoramic radar, operating on waves of the centimeter range.

In contrast to all other radiotechnical means of airplane guiding, airborne panoramic radar is unique in that it does not require any ground radiotechnical equipment.

The system is known as panoramic since it is used to make a survey (see panorama) of the terrain over which the airplane is flying. The operation of the panoramic radar set is based on the principle of measuring the distance between the aircraft and objects in the locality as well as on the intensity of reflection of radio waves from the locality and from the objects echoing radio waves.

The intensity of these waves produces, on the indicator scope, which is a

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cathode-ray tube, conventional representations of individual objects on the earth's surface (lakes, rivers, cities, bridges, mountains, railroads, etc.) and permits determining the distance and direction of these objects from the airplane.

Airborne radar thus permits to "see", permitting night orientation and orientation above the clouds; for this reason it can be used for bombing as well as for airplane guiding over given terrain, using the characteristics for "radiolocation" orientation.

2. Radio Beacons

The radio beacon (Fig.109) can operate both in a zone and on a bearing. For operation in a zone, two loop antennas are used whose plane traverses an angle

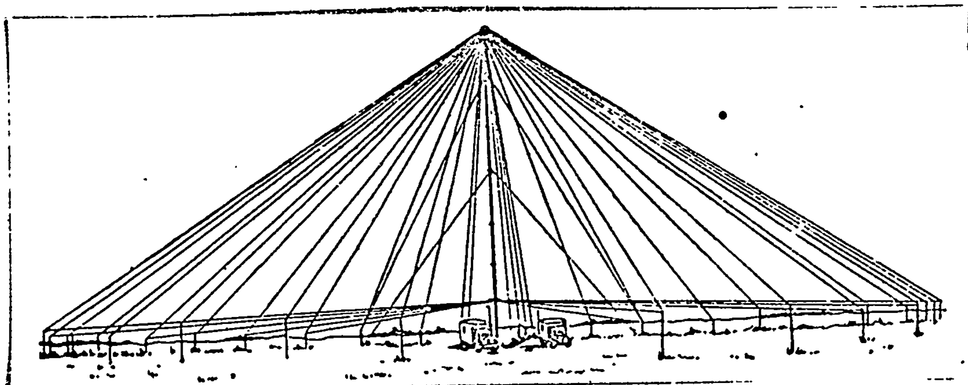

Fig.109 - Radio Beacon

of 135°; for operation on a bearing, 16 or 18 loop antennas are used whose planes traverse similar angles.

Operation of a zonal beacon consists in the following: Over the lines across each antenna, the beacon gives out signals by telegraph code. One antenna transmits the letter A, the other H. The signal strength of the letters A will be greatest if the direction beacon-receiver coincides with the plane of the antenna, using the signal A, and lowest (theoretically equal to zero) if its direction is perpen-

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dicular to that same plane. The same statement applies to the strength of the signal H, i.e., each antenna will have its own radiation pattern in eight lobes. Figure 110 shows the pattern of a radio beacon operating in a zone. Along the sides of the diagram are drawn the letters A and H which, by their size, characterize the signal strength in these locations. It is obvious that equally loud signals will occur only at the bisector AOH, indicated by letters of the same size.

Practically equally loud signals are located not only on the bisector, but also

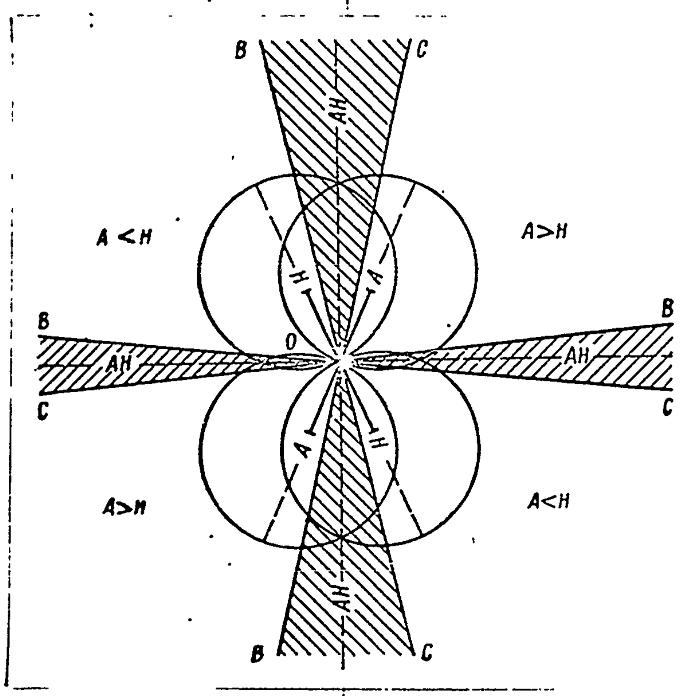

Fig.110 - Working Diagram of Radio Beacon Operating in a Zone

in certain sectors of BOC. This is due to the fact that the human ear is unable to perceive the insignificant variations in the intensity of the sounds. This sector is called the equisignal zone of the radio beacon. Two closed antennas of radio beacons form four equisignal zones (Fig.110).

Thus, the angular width of the zone, i.e., the angle through the vertex of the sector BOC depends on the angles of intersection of the plane of the antenna, namely the zone narrower than an obtuse angle, since two of the mentioned zones have an angular flare of 2 - 3° (the plane of the antenna intersects at an angle below 135°) while two others, perpendicular to the first, have a flare of 10 - 12° (the angle of intersection of the plane equals 180° - 135° = 45°).

Wide zones (more than 4 - 5°) are not used for airplane guiding since they do not guarantee the necessary accuracy; therefore, only two of four zones are used.

Radio beacon zones can be compared to the rays of a projector. Equisignal zones of radio beacons indicate a directional fix on the earth's surface, analogous to that possible with the aid of beams of a projector.

In equisignal zones, the audibility of the signals A and H is equal, while during deviation from the equisignal zone the audibility of one signal will be lessened and the other increased. Thus, the relative loudness of the signals can be used for estimating whether an airplane is located in the zone of the radio beacon or outside it, to the right or to the left.

If an airplane is so flying that the telephone gives the letters A and H with equal intensity, then the path of the airplane coincides with this zone; consequently, it can be used as "invisible rails" along which the airplane will be moving from one point to another.

The operation of a bearing beacon is as follows: Along lines through each of 16 or 18 antennas, the beacon radiates signals in telegraph code. Each antenna has its own definite signal being transmitted over definite time intervals. The rate of transmission is 30 - 60 signals (letters) per minute. The sequence of transmitting antenna is one hour. This means that 16 or 18 letters are transmitted into space successively. Since each antenna is a loop, at the moment of its transmission, it transmits in two directions at maximum audibility (in the plane of the loop) and in two directions at minimum (theoretically zero) audibility (along the perpendicular to the plane). Consequently, in all there will be 32 directions of maximum and 32 directions of minimum signals (or 36 directions through 18 loops).

In placing the beacon, the plane of the antenna is rigidly oriented relative

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to the Meridian of the location. Consequently, the minimum and maximum loudness of the signals will be found by strict determination of the direction from the beacon. If a radio receiver is set to a radio beacon operating by bearings, 16 or 18 letters will be heard in the telephone over a single interval of time; the known loudness of the letters will be different, one letter will sound loudest (the plane of its antenna coincides with the direction to the receiver) and one letter will sound least or be entirely absent (the plane of its antenna is perpendicular to the direction of the receiver).

Knowing the location of the radio beacon situated in the plane of the antenna with reference to the Meridian and the appropriate antenna letters, it is possible through the disappearance of the letters to determine the direction from the radio beacon to the receiver, i.e., to determine the bearing of the radio beacon from the airplane.

Since the plane of the antenna is rigid with respect to the Meridian and forms an angle of 11°15' (or 10°) then the perpendicular to it is located in a corresponding arrangement in space. Marking the perpendiculars of any letters not audible in the direction of these perpendiculars, will give the following scheme for the sequence of transmitting letters (Fig.111).

As is known, the audibility of any radio station diminishes as we move away from it. This also happens in the radio beacon. Naturally, the loudness of weak signals decreases first and the farther the observer is from the radio station the fewer letters he can hear.

From the above statement it follows that a radio beacon, operating on bearings, can be used as a means for determining the line of flight of airplanes or as a method of keeping the aircraft in the beacon or away from it. This requires a determination of the vanishing of letters and an accurate plotting of the line of bearing of these letters on the chart.

The lines received will be lines of the position of the airplane. In addition,

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for guiding the airplane to the radio beacon or away from it, the aircraft must be so piloted that the vanishing letters are always letters on the line of bearing, coinciding with the lines of the set course.

By placing two radio beacons in the zone of flight, it is possible to use these

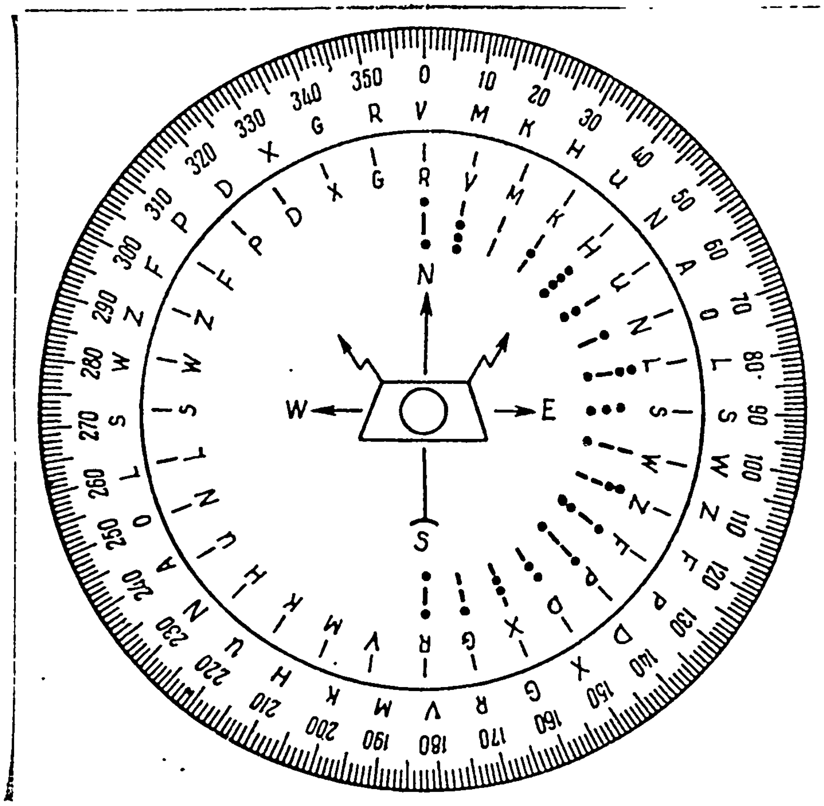

Fig.111 - Grid for the Radio Beacon .

for determining the location of the aircraft. In reality, each of the radio beacons makes it possible to locate the line of flight of the airplane, whose intersection gives the location of the aircraft.

3. Airborne Radio Direction Finders

At present, the most prevalent of all airborne direction finders is the automatic radio compass.

The automatic radio compass is used in the aircraft:

1) To determine the course angle of a transmitting radio station;

2) To pilot airplanes along a continuous course angle, relative to a given radio station.

The first function of the radio compass, to determine the course angle of the radio station, is used in conjunction with a magnetic compass to measure the true

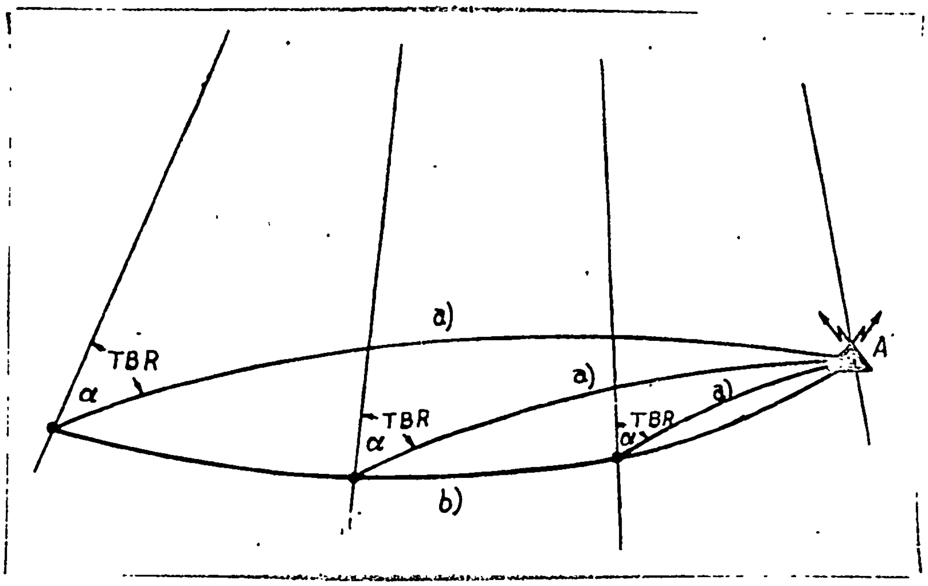

Fig.112 - Lines of Equal Radio Bearings

a) Line of bearing; b) Line of equal radio bearing

bearing radio station from the airplane.

Since radio waves propagate orthodromically between the transmitter and the receiver, the direction (true bearing radio station, TBR) determined by the radio compass is the orthodromic (great circle) direction.

The true bearing of the radio station is not in relation to the aircraft but in relation to the earth's surface. If, on the earth's surface, all the points in which the true bearing of the radio station is the same magnitude are connected by a smooth curve, then the curve obtained will be the line of equal radio bearing. This curve has the characteristic that the true bearing of the radio station, at any

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of its points, has the same constant magnitude.

Figure 112 shows a radio station located at point A.

If any true bearing α from this radio station is selected, then at each Meridian exists only one point in which the true bearing radio station (TBR) equals the set value α. By locating these points at each Meridian and by joining them with an ellipse we obtain the lines of equal radio bearings, characterized by the magnitude of the bearing α.

For bearings of any magnitude the radio station obtains the lines of equal radio bearing; it is easy to understand that lines of equal radio bearing merge with the Meridian of the radio station.

Thus, a radio compass in conjunction with a magnetic compass is used to determine in flight the line of flight of an airplane.

From radio stations it is possible to emit an enormous number of lines of equal radio bearings. But since the TBR is determined at the airplane in whole degrees, it is logical that, from each radio station, 360 lines of equal bearing with magnitudes from 0° to 360° are emitted. For facilitating the work in the air it is possible, before the flight, to plot lines of equal radio bearings of these stations on the chart, which serve for setting the bearing. Then in flight, having been assigned the TBR, the line of flight of the airplane can be determined. If, also in flight, the true bearings of two radio stations is determined, the point of intersection of the corresponding lines of equal radio bearing, gives the position of the aircraft.

A model of these charts is shown in Fig.113. These charts cover the area of Kirov – Archangelsk – Ust – Urt. Lines of equal radio bearing, extending across 10°, however, are difficult to interpolate and their accuracy will lie within the limit of the accuracy of the radio bearing.

Let us assume, for example, that in a flight the true bearing radio station, located in Archangelsk, is determined. This bearing is found to be equal to 320°. Consequently, the line of flight of the airplane, in this case, will appear as a

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curve (line of equal radio bearing) passing through points of the location of the radio station in Archangelsk and designated the number 320°. It should be mentioned

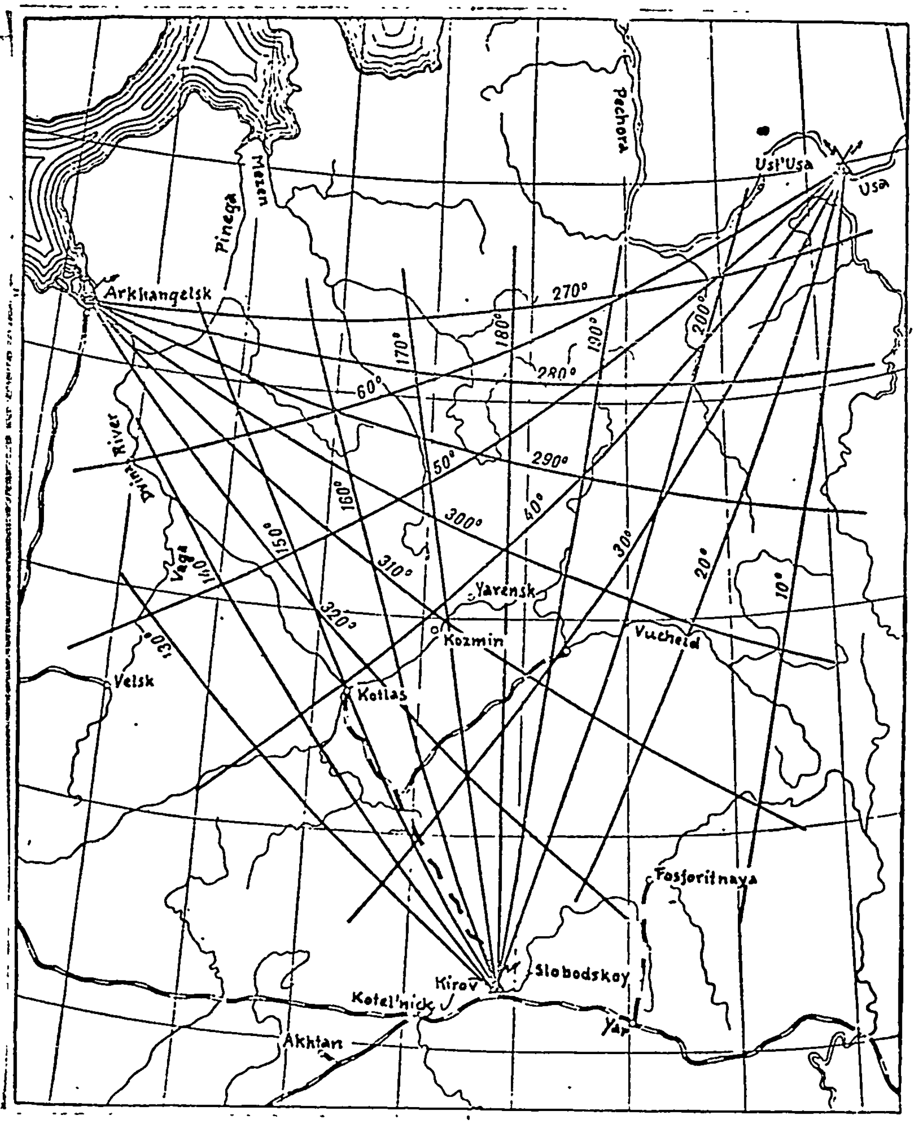

Fig.113 - Lines of Equal Bearing on a Map of Polyconic Projection

that, in view of the presence of errors inherent in radio direction finding, we obtain not lines but a strip, whose width is proportional to the magnitude of the error and the distance from the radio station.

By getting fixes at one time on two radio stations and obtaining thus two position lines, we determine the location of the airplane.

For example the true bearing: Archangelsk radio station of 310° and that of Ust-Urt radio station of 39, indicates that the airplane is located in the area of Kosmin. For a more accurate determination of the airplane location it is necessary to get bearings of all three radio stations. For example, the true bearing of the Archangelsk radio station is 306°, Ust-Urt 39° and Kirov 175°. Interpolating by eye, we find the location of the airplane in a point at Uransk.

The other application of the radio compass, namely piloting an airplane along a set course angle relative to the radio station, is obtained by the same wide emission during flights to the radio station. In flight, when the course angle of the radio station is constantly maintained equal to zero, the airplane will be guided to this radio station under any visibility conditions*.

The reckoning, which is done by the course-angle indicator of the radio compass, in general does not actually coincide with the known course angle of the radio station, but differs from it by some value, i.e., the radio compass, mounted on the airplane, inaccurately indicates the direction to the radio station. This difference between the true course angle of the radio station and the reckoning by radio compass (abbreviation ORK) is called the radio deviation and is denoted by

$$\Delta_p = KUR - ORK.$$

This relation is explained in Fig.114. There are both positive and negative radio deviation in existence.

Radio deviation is caused by the change in direction of the arriving radio waves by the metal parts of the airplane in which, due to the influence of the radio waves, an electromagnetic force is created. Thus electromagnetic energy, emanating from the radio station and encompassing the frame of the metal parts of the

*The radio compass ia also used,in flights from the radio station, but only when the direction finder coincides with the magnetic compass.

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airplane is acting on the frame. Therefore, the frame indicates the direction of the summary effect of the electromotive force. In order to determine the actual course angle of the radio station, it is necessary for reckoning by radio compass to increase algebraically the amount of radio deviation, corresponding to that reckoning, i.e.,

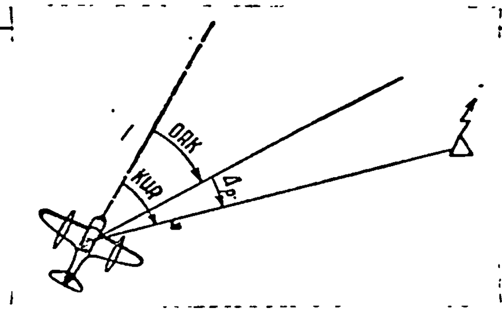

Fig.114 - Radio Deviation

$$KUR = ORK + \Delta_p.$$

If the proper meaning of ORK is required in order to learn the course angle of the radio station, it is necessary to deduct the value of Δ_p from the magnitude of KUR

$$ORK = KUR - \Delta_p.$$

The magnitude of the radio deviation depends on the distribution of metal parts

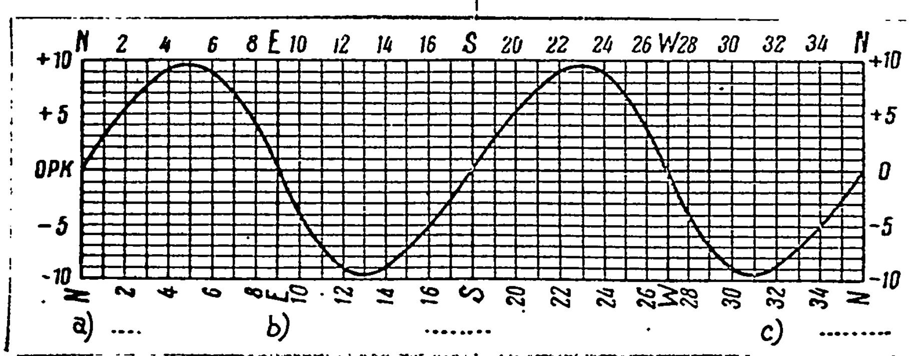

Fig.115 - Curve of Radio Deviation (Radio Deviation is not Compensated)

a) Data; b) Deviation RK of the pilot; c) Deviation RK of the navigator

near the frame of the radio compass, i.e., on the type of airplane and the location of the loop on the airplane. The amount of radio deviation changes also according to the course angle of the radio station, i.e., on the magnitude of the angle of the rotating loop. When the dependence of Δ_p on ORK is plotted graphically, a curve is obtained (Fig.115), which is the curve of radio deviation (analogous to the curve of deviation of the magnetic compass). Along the horizontal axis of the graph, the value of the radio compass reckoning (ORK) is plotted; along the vertical axis, the appropriate reckoning of the radio deviation (Δ_p) is shown. For example, if ORK = = 60° then we have $\Delta_p = 9°$, while if ORK = 150° we have $\Delta_p = -7°5'$, etc.

The appearance and shape of the curve of the radio deviation in Fig.115 characterizes, in a general manner, all curves of the radio deviation.

The curve is of the so-called quarter character, i.e., it changes its sign at each 90° (quarter circle) and has the greatest value at course angles of 45°, 135°, 225° and 315°.

The maximum amount of deviation occurs at 20 - 25°.

In placing the frames of the radio compass on the airplane, a location should be selected in which the radio deviation does not exceed the above figure and, if possible, is within the limits of 10° - 15°.

Radio deviation can be determined on the ground or in the air.

On the ground, radio deviation is determined visually or by remote radio station. For visually determining radio deviation, a radio station is required for locating the airplane within 2 - 3 wavelengths, by which the radio deviation is determined. For example, to determine the radio deviation at a frequency of 300 kc corresponding to a wavelength of 1000 m, the radio station must be no closer than 2 - 3 km to the airplane. However, it is impossible to determine the radio deviation in the vicinity of power stations (10 kw and over) since these may cause errors, due to distortions entering the electromagnetic field of the radio station.

The best way to determine radio deviation is by using an airfield radio station as the reference point, i.e., measuring the course angles of the station mast by means of a deviation direction finder and at the same time taking radio compass readings. For this purpose, the aircraft should be positioned at various course angles toward the radio station. The positioning of the aircraft, of the deviation direction finder, etc., is done as in the determination of magnetic compass deviations. Special attention should be paid to ensuring that the 0° and 180° calibrations on the deviation direction finder are rigorously parallel to the longitudinal axis of the airplane. For determining radio deviation there must be no high-tension lines, forests, etc. within a radius of 300 – 400 m of the aircraft's point of location. Before determining the radio deviation, it is necessary to make a check and remove discovered errors in the radio compass, which were created by placing the frame outside the plane of electrical symmetry of the airplane (usually coinciding with the mechanical plane of symmetry) or by incorrect setting of the frame or by both causes at once. Radio deviation may be determined from any course angle.

Results of determining radio deviation are shown in the Table below.

No. of Reading	KUR	ORK	Δ_p
1	0°	359°	+1°
2	15	10	+5
3	30	33	−3
etc.			

Determining the radio deviation for 24 course angles forms a radio-deviation curve just like the curve of deviation of a magnetic compass.

Unavoidable errors in the process of determining radio deviation give a certain scattering of points, plotted on a graph. Usually the plotting of points determines the slope of the curve and the curve can be extended by obtaining additional points without difficulty. A single scattered point has no great significance. Points are permitted to depart from the middle of the curve by not more than 1 – 2°. If, after obtaining fixes, it is difficult to plot the curve or if the points deviate from the slope of the curve by more than 1 – 2°, a new radio deviation must be determined.

Knowing the curve of radio deviation, it is easy to determine the course angle of the radio station. For example, using the curve of radio deviation, derived in

Fig.115, we find

For ORK = 70°, we have

$$\Delta_p = +7^{\circ};\ KUR = 70^{\circ} + 7^{\circ} = 77^{\circ}.$$

To know and to take into account the radio deviation is extremely important; by making a mistake of 1°, for example, an error of 15 km results in determining the location of the airplane at a distance from the radio station of 500 km. Since radio deviation may reach $15^{\circ} - 20^{\circ}$, it is clear that, in the absence of a curve of radio deviation or at incorrect radio deviation, using the radio compass is not only absurd but often unsafe. It is true that, at present, radio compass deviation, with the aid of special devices, is compensated to a lesser degree, but this is seldom taken into account during the flight.

Investigations have shown that radio deviation in the frequency range of the radio compass is practically independent of the frequencies of the radio signal being received; therefore, the curve of radio deviation, taken at a given frequency, will conform to all frequencies of the range of the radio compass. It has been shown that radio deviation does not depend on the altitude of flight; it is known that radio deviation, determined on the ground, other conditions being equal, is not different from radio deviation determined in the air. Therefore, radio deviation can be determined on the ground at any frequency. Sometimes in flight, the position of a given aircraft, equipment, or armament, in relation to some frame, may differ from that on the ground. In these cases it is necessary to determine radio deviation in the air. But such cases are sufficiently rare, and the greatest part of radio deviation is constant.

Frequently, radio deviations are determined by invisible distant stations. In these cases, the course angle of the radio station is determined not by direct bearings but by indirect means. To explain the manner of determining the course angle to the given radio station, we will quote some known correlations

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$$KUR = TBR - IK$$

so that

$$TBR = MPR + \Delta_M \text{ and } IK = MK + \Delta_M$$

Then we obtain

$$KUR = MPR - MK$$

Thus, knowing the magnetic bearing of the radio station in a given area and determining the magnetic course of the airplane, it is possible on the basis of this algebraic difference to calculate the course angle of the radio station and, knowing ORK, corresponding to this KUR, to determine Δ_p by the formula

$$\Delta_p = KUR - ORK$$

The magnitude MPR is constant for a given place and a given radio station and is easily determinable on a map of polyconic projection. In order to determine the MPR radio station at a given location, it is necessary to draw a straight line to the radio station at the point for which MPR is determined. Measuring the angle between the meridian of the given place and the direction (rectilinear) to the radio station, we obtain the TBR and, deducing from this the meaning of Δ_M for the given place, we obtain MPR.

The course of the airplane is determined by the bearing of remote orientation just as it is determined by deviation of the magnetic compass.

By determining radio deviation in the air a radio station and a line of orientation are selected. A distance between the radio station and the line of orientation of not less than 100 - 150 km is desirable, to have determination of the line of orientation coincide with the direction to the radio station.

On days when the air is calm, a flight can be made by orientation intersecting

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it with another course. At the moment of intersection of the lines of orientation the navigator takes a reading by the radio compass and the course angle of orientation. The received data is processed as shown above.

Special attention must be given to strict holding to the course. The airplane can be guided by an autopilot which can be switched on every time after bringing the aircraft to a "working" course, and switched off (for a more rapid execution of turns) during turns to new courses.

Automatic Radio Compass

The automatic radio compass has a loop which is automatically set toward the radio station for which the receiver of the compass is tuned. The angles of turn of the loop are transmitted to the pointer instrument which indicates the radio station angles of approach.

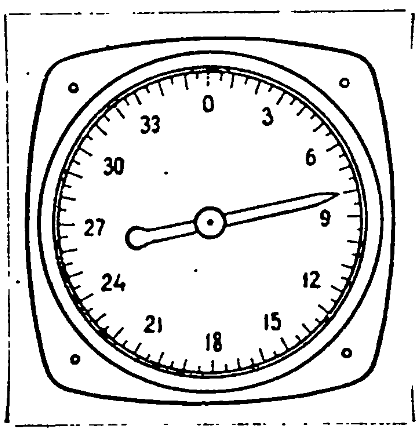

Fig.116 - Course Angle Indicator of the Pilot

Radio deviation in the radio compass is also taken into account automatically by means of a special mechanical compensator. Thus, in order to determine the radio station angle of approach it is necessary only to tune in on it and to take a reading on the dial of the course angle indicator.

The radio compass has a receiver, a converter, a loop, an open antenna, two control panels (the receiver can be controlled independently from two places: from the pilot and from the navigator) and two course angle indicators (one for the pilot, the other for the navigator).

The course angle indicator of the pilot is shown in Fig.116.

The course angle indicator of the navigator (Fig.117) is larger than the pilot's indicator, and its dial can be rotated by hand for setting the true course

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of the airplane.

Thus, by means of this device it is possible to sum up automatically the radio station angle of approach with true course of the airplane, i.e., to determine the true bearing of the radio station.

The frequency band of the radio compass constitutes 150 - 1750 kc.

The operating range of the radio compass depends on the power of the ground radio station and extends to 200 - 300 km for homing stations and 600 - 800 km for broadcasting stations.

The control of the radio compass is concentrated in one control panel (Fig.118).

For determining the radio station angle of approach is necessary:

a) To connect the radio compass by turning switch 11 to position "Antenna";

b) Verify the connection of the compass by observing whether the green signal light 9 is on; if light 9 does not glow, press control button 12; this button transfers control from one control panel to the other;

c) Establish the proper band by throwing the switch (3);

d) Turn volume control governor to its right-hand rest;

e) By rotating the handle of the tuning knob (10), determine the frequency, tuning it by ear and following the reading of the tuning indicator (5); the moment of resonance of the tuning is determined by the maximum deflection of the indicator needle to the right;

f) Verify by ear (by call signals) whether the tuner is performing on the necessary radio station;

g) Set the switch (11) to position "Compass";

h) Take a reading from the dial of the course angle indicator - and that will be the radio station angle of approach.

To determine the true bearing of the radio station by rotating the hand lever on the course angle indicator the navigator sets against the triangular index the

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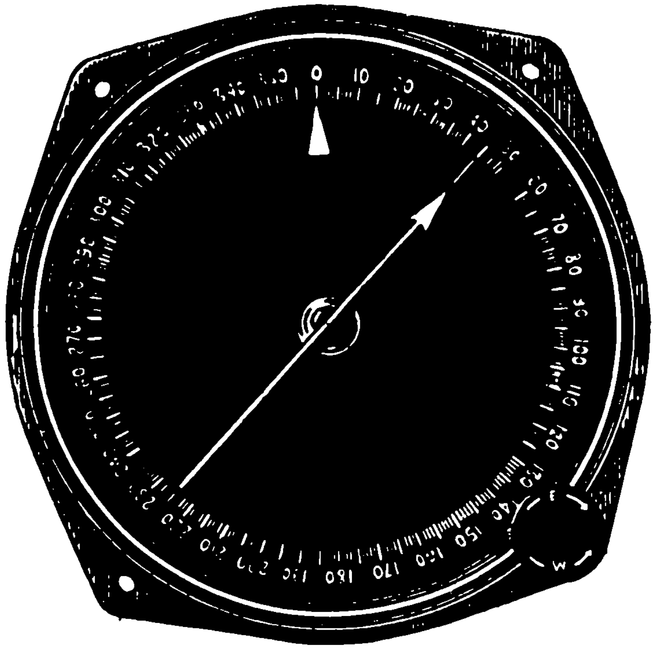

Fig.117 - Pilot's Course Angle Indicator

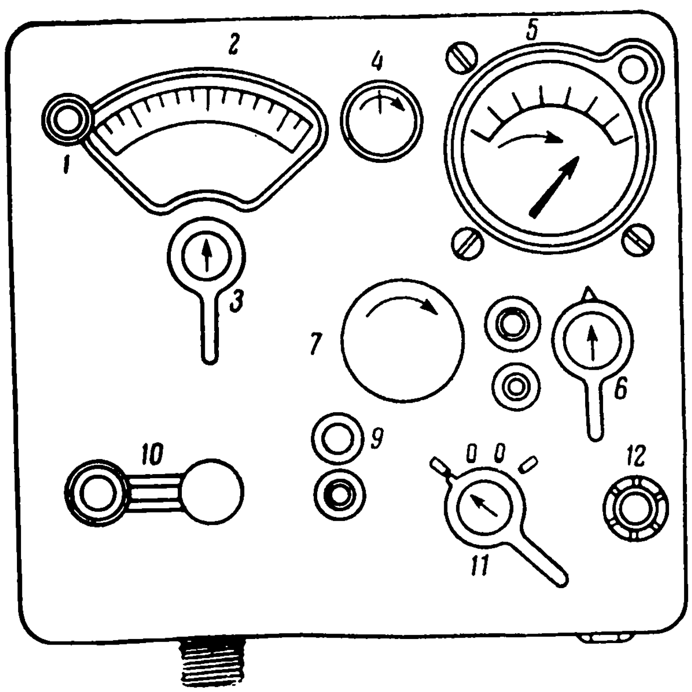

Fig.118 - Radio Compass Control Panel

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value of the true course of the airplane. The reading opposite the tip of the dial pointer is the true bearing of the radio station.

For a more exact determination of the bearing it is expedient to determine separately the mean values of the magnetic course and the course angle during 0.5 – 1.0 minutes, with subsequent summation of these values.

For a flight to the radio station it is necessary to guide the airplane so that pointer of the course angle indicator will be at zero all the time. If the pointer deviates to either side or zero, turn the airplane to that side so as to cause the pointer to return to zero.

The radio compass can be used as an ordinary receiver (for example, for hearing a radio beacon). For this purpose switch 11 is set in position "Antenna" thereby disconnecting the loop circuit and reception is obtained only on the antenna, by ear.

Conversely, it is possible to disconnect the antenna circuit and effect reception on one loop. This is achieved by the setting switch (11) in the position "Loop".

Reception on one loop is conducted either at considerable static interference with the usual reception on an open antenna, or for auditory direction-finding of the radio station by minimum audibility.

The rotating of the loop in this case is effected with the help of the knob 6.

For auditory direction finding it is necessary to rotate the loop so as to locate the minimum audibility of the station. For this purpose lever (6) is turned to the left and to the right, gradually reducing its deflections according to the minimum audibility of the signals of the station. On determining this minimum, the turning of lever (6) is to be discontinued and a reading is to be taken according to the course angle indicator.

Special necessity for direction finding by ear may arise in case of damages to the open antenna, for example its breakage owing to ice formation.

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Flight to the Radio Station

If at the terminal point of a flight route there is located an operating radio station with a frequency lying in the band frequency of the radio compass, then that compass can be used to accomplish the simplest and most reliable method of flying to that point-flight to the radio station.

The reliability of the method of flight to the radio station consists in that the airplane arrives exactly in the area of the terminal point of the route independently of conditions of landmark visibility. This is a convenient method for use on single seater airplanes. The value of this method lies also in that when it becomes necessary in flight to turn from the set flight path (for example, to by-pass a thunder storm), the radio compass makes it possible to return from any point of such deviation back to the flight path toward the radio station situated on an airfield. For this it is necessary only to tune the radio compass receiver to the radio station and fly the airplane so that the pointer of the course angle indicator remains at zero.

It is important during this to keep in mind, that during the flight to the radio station it is necessary to guide the airplane by magnetic compass, since without this it is not possible to compute the path traversed by the airplane. The radio compass can get out of order for some reason and then, if one does not follow the reading of the magnetic compass and does not compute the course, it is possible to lose bearings.

If the terminal point of the flight route cannot be detected visually, when the flight to the radio station proceeds at no ground visibility, the moment of passing over the radio station can be determined by the behavior of the course angle indicator pointer, which turns 180° at the moment of passage of the airplane over the radio station.

The electromagnetic energy radiated by the radio station propagates in arcs of large circumference, therefore the path of an airplane flying to a radio station by means of a radio compass must coincide with a great circle arc, connecting the place of take-off with the location of the radio station. However, this occurs only in calms or during favorable (head) winds. In all other cases, when the direction of the wind is at some angle to the direction of the great circle arc, the path of the plane relative to the earth's surface will not coincide with the arc and will represent some (radiodromic) curve as illustrated in Fig.119.

It is obvious, that the shape and size of this curve depend on the speed of the airplane and wind velocity and on the angle between wind direction and direction of route AB, in other words, it depends on the height of the ratio of airplane speed to wind velocity $n = \frac{V}{U}$ and on the wind angle ε.

Figure 119 depicts the curves of flight to the radio station for various values of n (the wind angle is constant and equal to 60°) and Fig.120 - the curves

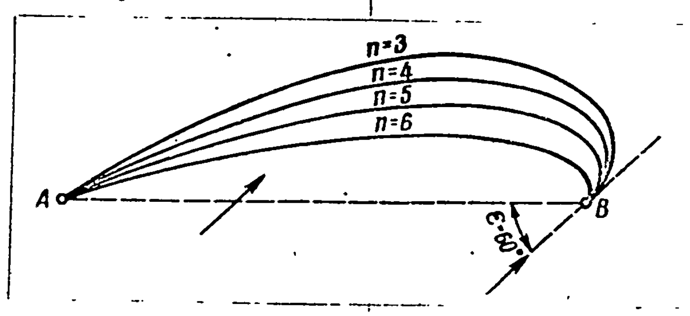

Fig.119 - Radiodromic Curves for Various Quantities n

of flight for various values of wind angle ε (n is constant and equal to 5). Examining Figs.119 and 120 it is possible to make the conclusion that the presence of a wind increases the length of the route and consequently, the flight time, and changes the course of the airplane (Fig.119). The latter is explained by the circumstance that the axis of the airplane is directed all the time toward the radio station (radio station angle of approach = 0°), whereas the airplane itself moves along a curvilinear path.

Such a flight to the radio station when the drift angle is not taken into account by the crew, has been termed passive flight.

The curves depicted in Figs.119 and 120 indicate that during a passive flight the airplane arrives at the radio station, after having turned against the wind. In actual flight conditions this does not happen. In order to follow exactly along

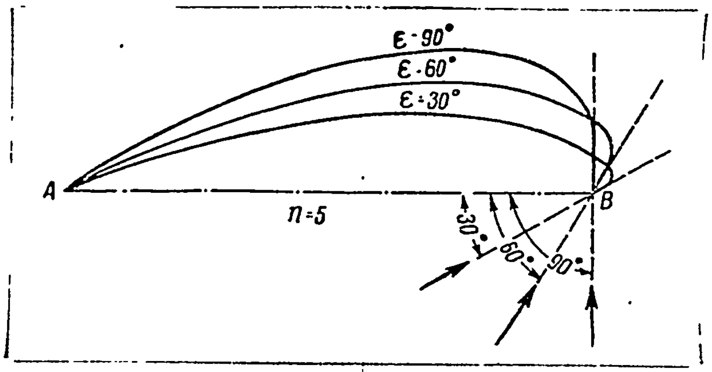

Fig.120 – Radiodromies for Various Values of ε

the radio dromy, it is necessary in the vicinity of the radio station to decrease very greatly the radius of turn (to increase bank up to 70 – 80 degrees and over) which in practice is impossible, and the airplane arrives at the radio station without succeeding in turning to the plane of the wind.

In order for the airplane to fly along path AB (Fig.119) it is necessary to effect an active flight, i.e., to take into account the drift angle and to guide the airplane at a course angle equal to

$$\text{Radio Station Angle of Approach} = 360^\circ \pm \text{Drift Angle}$$

where the plus sign means drift to the right and the minus – drift to the left.

During an active flight the length of the path traversed by the airplane is somewhat shortened, and, consequently, the flight time is reduced. However the main advantage of active flight lies not in this (the reduction of flight route and time being insignificant) but in, that during an active flight the airplane travels along the line of a given route or in its vicinity, whereas the flight along a radiodromy leads sometimes to considerable deviations from the given route. During and active flight it is easier to make a calculation of the progression by the

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plane on the route, this being an essential requirement for the crew carrying out a routine flight.

Therefore in all cases, whenever possible (when it is possible to determine the drift angle) flight to the radio station should be realized by the active method, turning to passive flight in the immediate vicinity of the radio station.

Pilots of single seater airplanes, flying, as a rule at a short distance from their aerodromes and not having the possibility to determine during the flight the drift angle of the radio station, resort basically to passive flight for arriving at the radio station of the landing aerodrome.

<u>Flight From the Radio Station</u>

Persons poorly acquainted with the radio compass, imagine that the radio compass can be used during flights from the radio station just as during flights to it, that is to guide the airplane toward a target on maintaining a constant course angle equal to 180°.

It is to be noted first of all that a flight from the radio station by the radio compass course angle indicator is impossible and the radio compass in such a flight plays merely the role of a direction finder.

The above is illustrated in Fig.121.

In this drawing A is the point of departure and B is the terminal point of the route. The straight line AB is the line of the assigned route. At absence of wind in flight it is necessary for the course of the airplane to be set in position 1 with the indicator pointer at zero. At deviation of the airplane from the course to the right (position 2) or to the left (position 3) the indicator pointer is deflected accordingly to the right (indicates less than 180°) or to the left (more than 180°) that is, it gives accurate readings. At the presence of a drift (position 4 or 5) the indicator readings will be the converse of the deviation of the airplane from the line of flight. Setting the needle indicator on radio station angle of approach = 180°, by turning the airplane in the necessary direction (according to the reading of the indicator pointer) leads the airplane into position 6 or 7. Thus the airplane will fly along another course. If the airplane is guided according to the course angle indicator during the flight from the radio station,

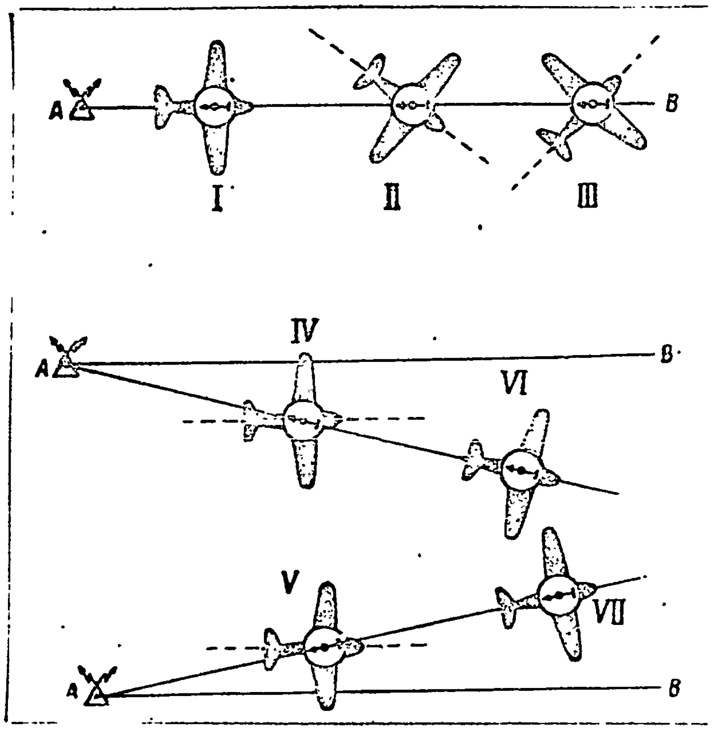

Fig.121 - Flight from the Radio Station

then the course of the airplane will fluctuate until the longitudinal axis of the airplane ceases to lie in the plane of the wind. Consequently, it is impossible to fly the airplane from the radio station by the course angle indicator.

Although it thus is not possible to guide the airplane by the course angle indicator during a flight from the radio station the radio compass is used in conjunction with the magnetic compass to control the line of flight, if the flight is conducted along lines of equal radio bearings.

During the execution of such flights it is necessary to select a course sequence in order to maintain the following equality in the course of the whole flight

$$IK + KUP = TBR,$$

where TBR is the value of the bearing from the radio station target point from which the flight began.

Thus for example, when flying from Nar'yan Mara to Salekhard (Fig.122) from the radio station, it is necessary to select courses at which

$$TBR = IK + KUR = 287°.$$

The flight is carried out in the following manner.

The airplane passes over the radio station at TC = 107°.

In 5 - 10 minutes afterward the KUR is determined. If TBR = IK + KUR equals 287°, then the flight is continued on that same course; if TBR is greater or less than 287°. then the course is changed (increased if the measured TBR is less than the rated TBR and decreased, if it is more). Several subsequent course changes are so selected as to cause the airplane to follow the line of equal radio bearings passing through the target (Terminal Point of Flight Plan, KPM).

During the execution of flights from the radio station it will not always be possible to prepare charts by plotting of lines of equal radio bearings. In such cases it is sufficient to measure TBR at target point and to maintain this value in flight, remembering that during flight from the radio station TBR is increased during deviation of the airplane to the right from the rated TBR (course to be reduced) and is lessened during deviation to the left (it is necessary to increase the course).

Having the opportunity in the point of departure to pass over a radio station, it is easily possible to determine the drift angle. For this it is necessary to fly from the radio station on a course equal to the given track course, and in the course of 4 - 7 minutes to guide the plane according to the magnetic compass, on carefully maintaining the tracked course. During this period of time it is

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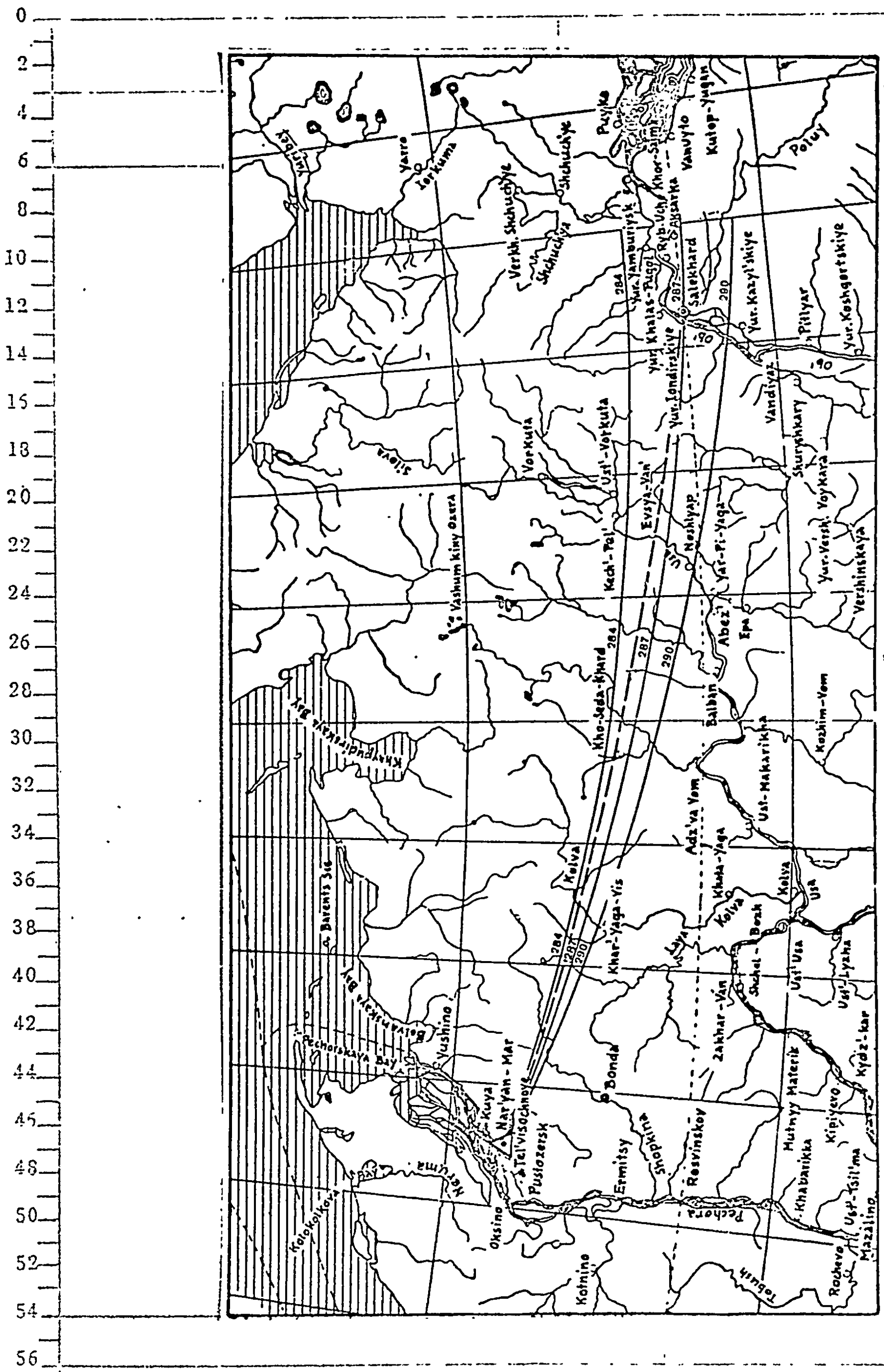

Fig.122 - Example of Flights from a Radio Station

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necessary to determine the radio station angles of approach (to take 5 - 10 readings) and then the algebraic difference between the mean arithmetic value of all course angle readings and 180° will yield the value of the drift angle on this course, with the sign of the difference indicating the direction of drift (plus to the right, minus to the left).

The above is illustrated in Fig.123.

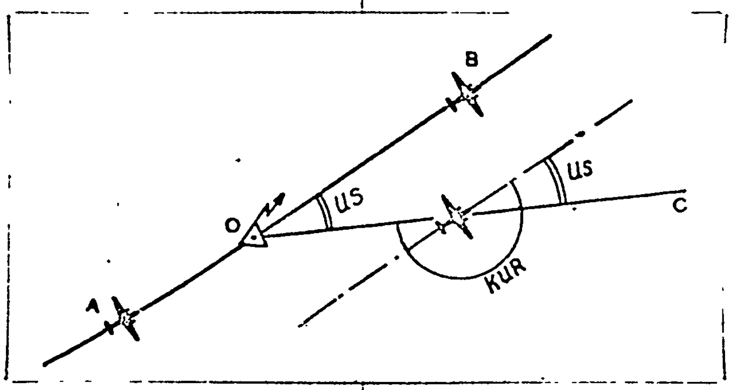

Fig.123 - Determining the Bearing Angle From a Flight over the Radio Station

Determining the Position Lines of Airplane

The procedure for determination of the position lines of an airplane by means of a radio compass consists in:

a) Tuning the receiver to the necessary radio station;

b) Maintaining strictly the flight course during a half minute (by means of an autopilot, if possible) so that at a calm state of the atmosphere the rhumb card of the magnetic compass would waver by not more than 1 - 2°, and at a disturbed condition of the atmosphere the card would waver uniformly in both directions relative to the mean course;

c) On verifying the correctness of the course (having determined the mean course), taking a bearing on the radio station and take the mean reading of the magnetic compass, remembering that "to take a bearing on the radio station" means

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"to take the mean reading on the dial of the course angle indicator";

d) Recording the readings of the magnetic compass and radio compass and the time of radio direction finding;

e) Advising the pilot of the completion of radio-direction finding and of the possibility of relaxing piloting; however, after the radio-direction finding the course should be strictly maintained in order to have the possibility of utilizing the obtained position lines at the time of completing the processing of the results of radio-direction finding;

f) Performing the calculations necessary for computing the true bearing of the radio station; it is convenient to tabulate these calculations:

	Station	
	No. 1	No. 2
Frequency		
Time		
KK		
IK		
KUR		
TBR		

g) Upon determining TBR, on a map prepared beforehand, to locate (or interpolate) the corresponding line of equal radio bearings.

That will be the position line of the airplane at the time of radio-direction finding.

If there is no chart prepared with lines of equal radio bearing, then such a corresponding line can be plotted in situ.

The bearing line determined by means of the radio compass, we will term an orthodromic line stretching from the radio station to the airplane. On standard charts it is depicted as a straight line. In order to plot it on a chart, it is necessary to compute from the known TBR the true bearing of the airplane, to plot this bearing from the northern side of the meridian of the radio station site and --

to draw a straight line under this angle; this will be the sought for bearing line on which the airplane is situated.

The true bearing of the airplane (IPS) for great distances does not equal TBR + 180°. The value of the true bearing of the airplane is determined by the formula

$$IPS = TBR + 180° + \sigma,$$

i.e., the true bearing of the airplane is equal to the true bearing of the radio station plus 180° plus corrections for convergence of meridians (σ). The correction for convergence of meridians is calculated by the formula

$$\sigma = 0{,}8\,(\lambda_p - \lambda_c).$$

The values of longitude included in this formula, must be taken in whole degrees with the rounding of the number of minutes to the nearest whole number of degrees. For example, if $\lambda = 37° 29'$, then this must be rounded off to $\lambda = 37°$ but if $\lambda = 37° 31'$, then make it 38°. Such a procedure involves errors not exceeding 0° 5 .

<u>Example 1</u>. $\lambda_p = 37°$; $\lambda_c = 30°$. Find correction for convergence of meridians σ.

$$\sigma = (37° - 30°) \cdot 0{,}8 = 5°{,}6.$$

<u>Example 2</u>. $\lambda_p = 40°$; $\lambda_c = 50°$. Find σ

$$\sigma = (40° - 50°) \cdot 0{,}8 = -8°.$$

The longitude known as a result of computing the course is to be taken as the longitude of the fix.

If the radio station is located east of the airplane, then has a positive sign and if west then negative.

Thus the absolute value of σ is added to TBR when the radio station is east of the airplane and subtracted when west.

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The process of determining the bearing line is as follows:

a) Calculate as indicated above the true bearing of the radio station (TBR);

b) Use the calculated TBR to determine the true bearing of the airplane by the formula

$$IPS = TBR + 180^\circ + 0{,}8\,(\lambda_p - \lambda_c);$$

c) At the point of location of the radio station on the chart, plot with a protractor, from the north side of the meridian, an angle, equal to IPS and plot under this angle a straight line from the point of location of the radio station – the bearing line.

The segment of this straight line in the area of calculated location represents the line of position of the airplane.

The scale of the chart is selected on basis of the same considerations as those followed in plotting the lines of equal radio bearings.

This method of determining lines of position is less accurate than the method of lines of equal radio bearings in view of the errors introduced in IPS owing to lack of knowledge about the exact value of longitude of the fix.

Determining the Fix of the Airplane

The fix of the airplane is determined by the point of intersection of two position lines. Being able, in the airplane, to determine the TBR of two known radio stations and having beforehand, before the flight, prepared charts with lines of equal radio bearings, we will find the fix at the point of intersection of the two lines of equal radio bearings, corresponding to the received bearings. To increase accuracy, it is necessary to home in on three radio stations.

Example. In-flight radio-direction finding of radio stations in Kirov, Archangel and Ust-Usa. The obtained data is given in the table:

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	Station		
	Kirov	Archangel	Ust-Usa
Frequency	250	180	465
Time	14 - 15	14 - 16	14 - 17
KK	42	44	42
IK	60	62	60
KUR	115	244	339
TBR	175	306	39

Finding on the chart (see Fig.113) the lines of equal radio bearings, we use the computed values of TBR to determine that the fix of the airplane at 14 hours and 16 minutes was in the region of Uransk.

If in flight the crew lack preflight charts and it is necessary to determine the fix by means of the radio compass, this can be done by plotting compass data on the chart of bearing lines.

Example. In-flight radio-direction finding of two radio stations: Leningrad ($\lambda_p = 30^\circ$) and Kazan ($\lambda_p = 44^\circ$). For the radio station at Leningrad ORK = 226°; $\Delta_p = +5^\circ$; for the station at Kazan ORK = 321°; $\Delta_p = -2^\circ$. The true course at the time of the direction finding was 100°.

Approximate longitude of the plane $\lambda_c = 38^\circ$.

To determine the fix of the airplane.

1. Find the IPS for the Leningrad radio station

$$KUR = 226^\circ + 5^\circ = 231^\circ;$$

$$TBR = 100^\circ + 231^\circ = 331^\circ; \sigma = (30^\circ - 38^\circ)\ 0.8 \approx -6^\circ;$$

$$IPS = 331^\circ - 180^\circ - 6^\circ = 145^\circ.$$

2. Find IPS for Kazan radio station.

$$KUR - 321^\circ - 2^\circ = 319^\circ;$$

$$TBR = 100^\circ + 319^\circ = 59^\circ; \sigma = (44^\circ - 38^\circ)\ 0.8 = +5^\circ;$$

$$IPS = 59^\circ + 180^\circ + 5^\circ = 244^\circ.$$

Compile it in a table as follows:

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	Station	
	Leningrad	Kazan
Frequency	271	458
λ_p	30^o	44^o
Time	10 hrs. 20 min.	10 hrs. 21 min.
KK	90^o	90^o
IK	100^o	100^o
KUR	231^o	319^o
TBR	331^o	59^o
λ_c	38^o	38^o
$\lambda_p - \lambda_c$	-8^o	$+6^o$
$\sigma = 0.8\ (\lambda_p - \lambda_c)$	-6^o	$+5^o$
IPS	145^o	244^o

3. We plot on the chart the bearing lines of the airplane and at their intersection we obtain the fix of the airplane in the region of Zadonsk (Fig.124).

The accuracy of the determination of radio station bearings in flight depends to a great degree on the quality of guidance of the airplane. Therefore at the

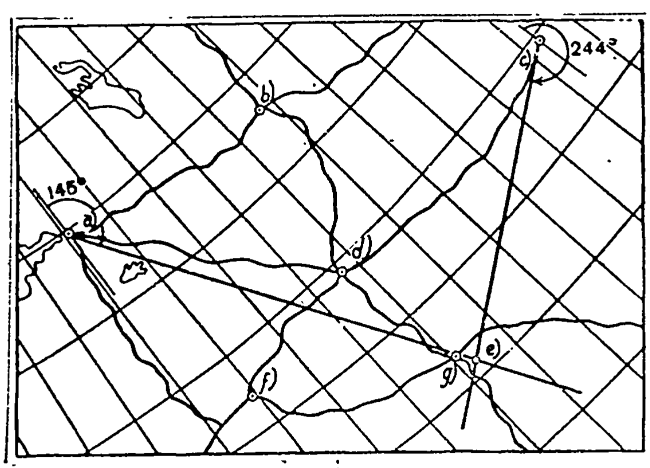

Fig.124 - Determining the Fix of the Airplane by Plotting Bearing Lines

a) Leningrad. b) Vologda; c) Kazan; d) Moscow; e) Zadonsk; f) Smolensk; g) Eluz moment of radio-direction finding the flier must apply all his skill and endeavor, in order to keep the airplane on course. However because of the wavering of the course it is not always possible for the pointer of the radio compass indicator to remain "immobile" for some time. In these cases it is necessary to average the deviations of the pointer to the right and left of zero. If the amplitude of oscillations of the pointer becomes too great, it is necessary to regulate the sensitiveness of the indicator. It is necessary, however, not to give the indicator too little sensitivity, since low mobility of the needle can lead to errors in course angle reading.

Only team work by the crew gives good results in radio-direction finding, therefore it is necessary to give as much time as possible to training in setting bearings of radio stations.

Note. During the determination of the fix of an airplane by means of a radio compass there passes a certain interval of time between taking the bearing of the first radio station and the bearing of the second, therefore, at the moment of taking the bearing of the second radio station the bearing of the first radio station actually changes by some value depending on the distance from the airplane to the radio station, the angle of approach of this radio station, and the speed of the airplane.

Thus, on plotting on the chart the bearings of the airplane from the first and second radio stations, we obtain a fix at fictitious point. This happens in consequence of ignoring the so-called "correction for time". This correction if of a substantial magnitude when the airplane is flying near the radio station and has a considerable speed. The correction reaches its maximum magnitude at course angles approximating 90°.

In certain cases it may become absolutely necessary to take into account correction for time. For this, the following procedure is recommended.

1) Find the bearing as usual, but on the chart transpose the line of the first

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bearing (or a segment of a line of equal radio bearings) parallel to itself along the direction of the course of the airplane by the extent of the path traveled by the airplane at the time of finding the bearing.

The point of intersection of the transposed first line of bearing with the second line of bearing marks the fix of the airplane.

2) From the first radio station get two bearings, one before and the other after the second station, so that the time intervals between the bearings would be as uniform as possible and less than one minute if possible and not more than one minute. By computing the arithmetic mean of the bearings of the first radio station, we obtain its bearing, relative to the moment of homing in on the second radio station, that is, we obtain the correct fix of the airplane.

Guiding the Airplane to a Set Line of Equal Radio Bearings

For the solving of certain navigational problems it becomes necessary to steer the airplane along a set line of equal radio bearings.

The necessity for this can arise, for example, when it is necessary to fly the airplane to a target along a line of equal radio bearing (LRRP) from a radio station located apart from the aerodrome, or when it is necessary to fly to the radio station from a specific direction not coinciding with the basic flight path, etc.

Since each LRRP is characterized by a definite value of TBR, the moment the airplane flies on the set line will be characterized by equality between the sum of IK + KUR and that value of TBR. Consequently, it is possible to approach the set LRRP from any course, and then the signal of arrival at that line will be constituted by the magnitude of KUR equalling

$$KUR = TBR_o - IK,$$

where TBR_o is the magnitude of TBR for the set line of equal radio bearing.

Suppose, for example, it is necessary to fly toward an LRRP, characterized by $TBR_o = 256°$; and the airplane course (true) equals 195°. We find that $KUR = TBR_o -$

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IK = 256° − 195° = 61°. Consequently, flying at a course of 195°, we will be situated on the set LRRP when on the dial of the course angle indicator (or automatic compass) will indicate a reading equal to 61°. It is obvious that if during a flight toward a set LRRP it is necessary to change the airplane's course, then the turn to the new course must begin with some lead prediction.

Wavering of the airplane on the course makes the course angle indicator pointer and the card of the magnetic compass waver; therefore it is necessary, first, to keep strictly on the course during approach to a set LRRP and, second, to take mean readings of the oscillations of the course angle indicator pointer and also to control the readings of the magnetic compass.

4. Ground Radio Direction Finders

A ground radio direction finder is a receiving radio station, possessing directional properties, and serves for determining on the ground in the location of its site the bearing of a flying airplane.

In Fig.125, at point P is situated a direction finder, CYu is the true meridian of its site, and at point A is an airplane; AP is the great circle arc (along which electromagnetic energy radiated from the airplane transmitter propagates toward the direction finder). The angle between the northerly side of the meridian of the site of the direction finder and the great circle arc is the true bearing of the airplane, which is measured by the direction finder.

In order to determine with the help of a direction finder the bearing of the airplane, it is necessary that the airplane's crew furnish radio signals and the crew of the direction finder station receive and take the bearings of these signals. For this, naturally, the airplane must have a radio transmitter. Since the bearings are determined in most cases for the benefit of the crew of the airplane, then, in order that the results of direction finding can be communicated to the plane, the direction finder or DF station should possess a radio transmitter, while the airplane must have a radio receiver. So, the means necessary for air-

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plane guidance by means of ground radio direction finder stations consist of:

a. In the airplane - a receiving-sending radio station;

b. On the ground - a radio direction finder and a transmitting radio station.

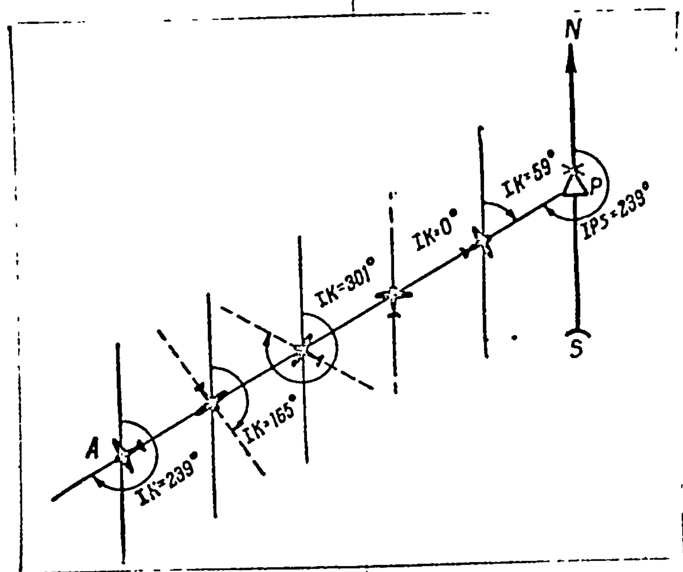

Fig.125 - Position Line of An Airplane Determined from a Ground Radio Direction Finder

For all airplanes, situated on a single orthodromic line, passing through the site of the direction finder, there will be one and the same bearing and it will not depend on the course of the airplane (see Fig.125) hence the reversed situation will also hold true; the airplanes located on one bearing, are located on one orthodromic line. Airplanes situated at different bearings are situated on different orthodromic lines. Thus the orthodromic line that is being determined by means of the radio direction finder, and that passes through the locus of the airplane and is characterized by the measured bearing, is a position line of the airplane.

Having the possibility to determine with the help of the radio direction finder the position lines of the airplane, it is possible to use this for the following purposes:

a. Control of the course in distance or in direction (along one position

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line);

b. Determination of the fix of the airplane by the intersection of two position lines;

c. Guidance of the airplane to the site of the radio direction finder;

d. Guidance of the airplane toward target area at flight from the radio direction finder.

The obtainment of good results of radio-direction finding demands precise and smooth team work between the crew of the airplane (radioman) and the personnel of radio direction finder, and reliable two-way radio communication, which for simplicity and conciseness is conducted by a special scheme using the internationally adopted Q-code. The true bearing of the airplane (IPC) is inquired for by the code phrase QTE and is plotted from the point of location of the radio direction finder for determining on the chart the position line of the airplane.

If it is necessary to guide the airplane toward the radio direction finder, the pilot, having obtained the IPC (QTE) can change it by 180° and, if necessary, introduce corrections for the difference in magnetic inclinations and the angle of convergence of meridians.

On charts, being used in air navigation (scales of 1 : 2,000,000, 1 : 1,000,000; 1 : 500,000), it is possible with sufficient accuracy to compute, that in the middle latitudes at distances of 1000 km and more the arcs of great circles are represented as straight lines. Therefore the position lines of the airplane determined with the help of ground radio direction finders are flattened out into straight lines on these charts.

In order to obtain position line of the airplane from the radio direction finder, it is necessary to plot on the chart at the point of location of the direction finder with the help of a protractor, from the northern direction of the meridian, an angle the equal true bearings of the airplane, and to plot a straight line at that angle. This will be the position line of the airplane at the moment the

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airplane broadcasts the signals for direction finding. Afterwards this line is used like any other position line.

Since the position line obtained on the chart, refers to locus of the airplane at the moment of broadcasting the signal for radio-direction finding, and since the receiving and the plotting of the results of radio-direction finding takes some time (3 or 4 minutes) then, naturally, it is necessary for exact orientation to take into account the progress of the airplane for that time. For this, it is sufficient to increase the air speed of the airplane at the time and parallelwise transpose the position line to that segment of the path traveled as according to direction of the airplane's course. Throughout all that time it is necessary to keep the airplane on a constant course.

Being able to determine the position line of the airplane by one radio direction finder, it is simple to determine the fix of the airplane by the point of intersection of two position lines from two radio direction finders.

For this it is necessary:

a. To obtain a bearing from the first radio direction finder;

b. To obtain a bearing from the second radio direction finder;

c. To plot on the chart the position lines of the airplane;

d. At the point of intersection of these lines to determine the center of the region of the probable locus of the airplane.

It is necessary to take into account the circumstance, that the bearings are taken by both direction finders at different times, therefore it follows that the line of bearing of the first is to be parallelwise displaced in the direction of the course of the airplane by the magnitude of the path traveled by the airplane during the time interval between the two bearings.

At frequent use of some ground direction finders in a given area, it is expedient to prepare a chart. The preparation consists of plotting orthodromic curves (straight lines on a map of conic projections) from points of location of direction

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finder stations and designating them by the corresponding numbers of bearings. Then in flight the necessity for graphical charting work decreases and the locus of the airplane on such a chart is determined fairly simply.

For facilitating the work of the airplane crew, the direction finders are sometimes joined into groups, consisting of two or several direction finders situated at some distances from each other, a control tower in communication with these direction finders and a sending - receiving radio station for communication with the airplane.

At such organization, the data concerning the bearing of the airplane is received from the direction finder at the control tower, where it is processed and are at once communicated to the airplane its coordinates. In this case the work of the airplane crew consists only in inquiring about the geographical coordinates by the code phrase QTF, and obtaining them from the control tower.

The ground radio direction finder, situated at the terminal point of a straight-line route, can be used by the airplane crew as a reliable means of controlling the flight path and of accurate guiding of the airplane to these points. For this it is necessary to fly the airplane so that its bearings, measured by the direction finder during the entire flight, are equal to the bearing at the point of departure. In other words, it is necessary to fly the airplane so that its flight path coincides with the orthodromic line passing between IPM and KPM. From the point of view of air navigation such a course is the most advantageous since it is the shortest.

As is known, during the execution of a flight along an orthodromic curve (which always happens at very long flights) the latter is replaced by a number of loxodromic curve plotted on it, the quantity of which is determined by the consideration that the track angles of the two adjoining loxodromic curves would differ from one another by a magnitude of not more than $3 - 4^{\circ}$. At the same time the adopted procedure is not to trace the loxodromic curve, but instead to

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represent it on the chart by a straight line, if the greatest deviation from this straight line does not exceed 5 - 10 km or if the difference in track angles at the

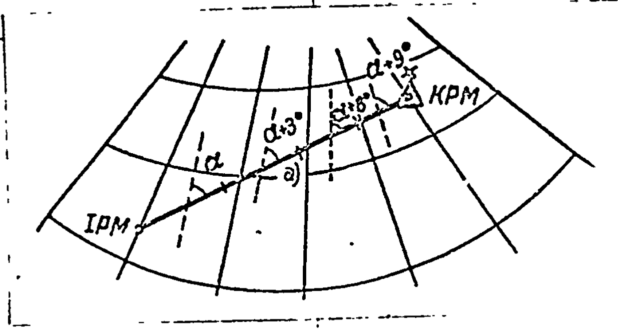

Fig.126 - Preparation of Chart for Flight to a Radio Direction Finder

a) Orthodromy

ends of the straight line does not exceed 3 - 4°. On conic-projection charts (and on the "millionth") used in air navigation, the orthodromic curve is represented with sufficient accuracy by a straight line, therefore the process of mapping on the chart a flight along an orthodromic curve consists in plotting a line (orthodromy) between IPM and KPM and dividing it into segments so that the track angles of every two adjoining segments, measured by the mean meridian of segment, differ from each other by 3 - 4° (Fig.126).

On flying the airplane at these track angles by the magnetic compass so that in the course of the whole flight the true bearing of the airplane is maintained constantly, we will bring it to KPM by the shortest route.

The moment of appearance of the airplane over a direction finder is determined by personnel of the direction finder by the engine noise, and is also announced by radio by the crew of the airplane. If no such notice is received by the personnel then the said moment is determined according to the change of the airplane's bearings by 180° (after flying over the direction finder).

During good visibility the time of passing over the direction finder is determined visually.

Determination of the angle of drift for calculating it on the tracking course is performed in the usual manner if the earth is visible and if it is invisible either by pilot balloon data obtained on the ground or by selection of the tracking course.

The order of executing an instrument flight to a direction finder is as follows:

a. Prepare a chart before the flight; plot a straight line (orthodromy) between IPM and KPM; divide it into segments and for each segment determine the track angle; on both sides of this straight line plot also bearing lines, separated from the first by 2°;

b. Plot a course equal to the track angle of the first loxodromy.

c. About 10 - 15 minutes after departure, ask for a bearing; if the received bearing equals the set one, continue the flight on that course.

Note. Change of course, suitable for transition from one loxodromy to another is performed at calculated times.

d. Periodically, about every 10 - 15 minutes request a bearing; if the bearing received does not agree with the set one, then reverse the course by $15 - 20^{\circ}$ and watch for a change to the received bearings.

If the first course change is too great or small (according to the bearing readings) change the course again (in the necessary direction) by $5 - 10^{\circ}$. By such successive course changes it is possible to select the necessary course and adjust the travel of the airplane to the set bearing line.

During the execution of such a flight the airplane should receive its true bearings (IPS) from the direction finder.

The flying of an airplane to a radio direction finder is often done without preflight charts, especially by the crew of single seater airplanes. In such cases the flight is thus executed:

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a. Having decided to guide his airplane to a known radio direction finder, the pilot requests the course to the direction finder (magnetic bearing of the radio direction finder, MPR); as for the multiseater airplane, the crew request the IPS, and the navigator himself computes the magnetic course to the radio bearing finder;

b. Having received this course, the flier sets the airplane on it and maintains it until receiving another course; the pilot inquires about another course in about 5 - 15 minutes (depending on the distance from the direction finder; the closer then the oftener the course must be asked. If the second course equals the first, the pilot continues to hold it, but if they are not equal, then he sets the airplane on the new course;

c. Thus, inquiring (periodically every 5 - 15 minutes) about the course, the pilot flies the airplane strictly on that course until he arrives at the radio direction finder.

The crew of the airplane during work with the radio direction finder must remember, that courses (or bearings) received from it refer to the time of sending the radio-direction finding signals for, therefore it is always necessary to take into account the progress of the airplane during the time interval elapsing between the time of sending a signal and the time of receiving and realizing the bearing data. Through non-observance of this, it is possible to commit an error, i.e., to relate the received bearing (or course) to the moment of its reception and not to the moment of sending the radio-direction finding signal.

Such errors may be quite important especially when the airplane is near the direction finder and when there is a long interval of time between the above mentioned moments.

During execution of a flight along a straight-line route, the radio direction finder, established at IPM, may be used for controlling the flight direction. Execution of such a flight differs little from executing a flight to the radio direction finder.

The difference between these is this that during a flight from the radio direction finder, the accuracy of determination of lines of lateral deviation worsens at an increase in the distance from IPM, and the point of arrival is not recorded by the radio direction finder itself. These two circumstances lessen the accuracy of determining the time of arrival at the target and therefore it follows that the changes of bearings are to be watched carefully and the airplane is to be always immediately returned to the given orthodromy (flight path) upon receiving a bearing different from the target bearing.

It is necessary well in advance of arrival at the target to select the necessary course in order to travel along the given orthodromy upon taking drift into

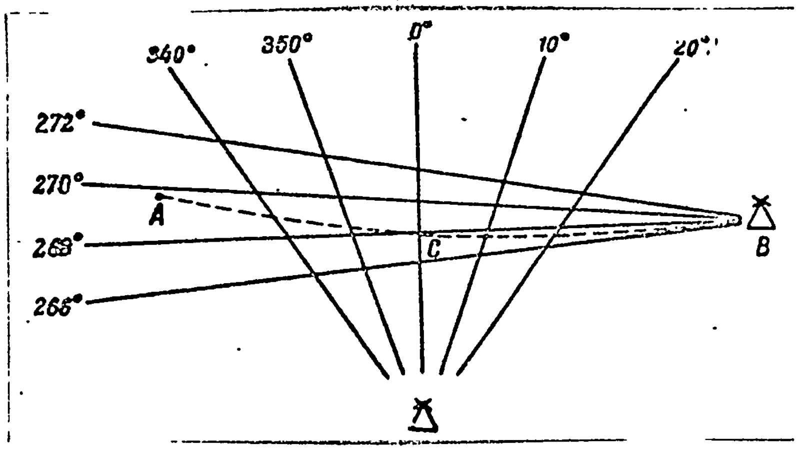

Fig.127 - Preparing a Chart for Flight From the Radio Direction Finder

account. Selection of the course is accomplished just as in a flight to the direction finder. It is especially necessary to watch carefully for the coinciding of the flight path with the set orthodromy during the approach to a target situated at a considerable distance from the direction finder, since in this case a small change in the bearing of the airplane corresponds to its large deviations from the target (KPM).

It is to be taken into account, that at distances of 150 - 250 km from the

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direction finder, there lies a zone of unstable bearings, in which radio-direction finding is either impossible, or involves considerable errors.

Control of flight distance is performed either by calculations or by lines of position from some other means of air navigation. In particular, it is possible to use bearings from other radio direction finders situated on a side of the route. For this it is expedient to use charts, prepared as shown in Fig.127. On these charts a series of orthodromies is plotted from a direction finder located at take-off point. In flight, after selection of the necessary course for a flight along a set orthodromy, a side direction finder is contacted for determining the ground speed of the airplane and the time of arrival at the target point (KPM).

5. Ground Radar

Ground radar is used to determine the bearing and distance of an airplane at the point of its installation and so determine the locus of the airplane. In effect, the determining the bearing of an airplane also determines a line of position of the latter, represented by the orthodromy passing through the installation point of the radar and the locus of the airplane. On establishing the distance to the airplane, the other line of position is determined; this other line is represented by a circle with its center at the radar installation point, and radius R, equal to that distance.(Fig.128). The intersection of these two lines of position definitely represents the fix of the airplane.

Being able to determine the locus of the airplane by means of radar, it is possible, by means of a series of successive points plotted onto the chart, to plot the flight path of the airplane and to determine the track angle and ground speed of the airplane (Fig.129). This can be done either by radar, communicating the prepared data to the airplane crew or in the airplane on basis of data received by the crew from the radio direction finder about distances, bearings and time moments.

The possibility of determining the locus and the flight path of the airplane

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with the help of ground radar permits employing the latter for controlling the execution of routine flights and for solving the following air navigation problems:

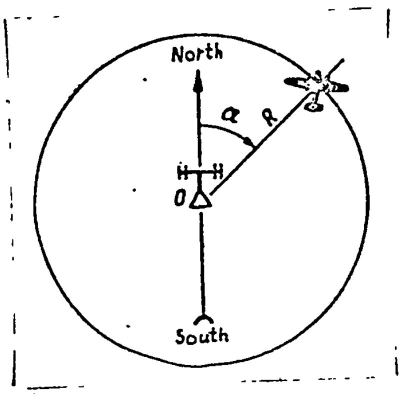

Fig.128 - Determination of the Fix

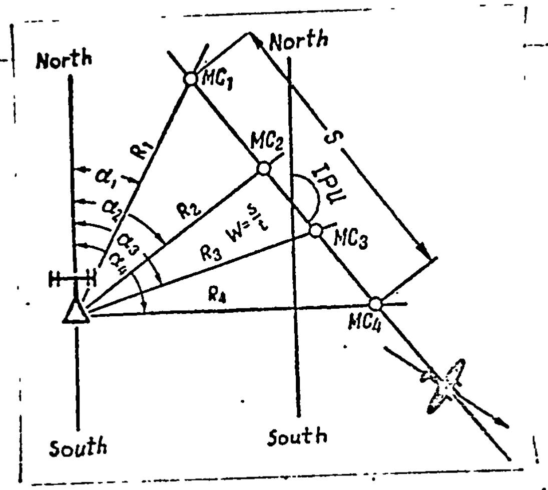

Fig.129 - Determination of the Track Angle and Ground Speed

a. Determination of the fix of the airplane (reestablishment of lost orientation);

b. Guidance of the airplane to the radio locator;

c. Guidance of the airplane to target area;

d. Determination of ground speed and track angle of the airplane;

e. Guidance of the airplane toward a landing airfield located apart from the radar site.

The solving of these problems does not depend on the time of day and can be executed in any visibility conditions, which makes ground radar especially valuable for executing flights without visible ground landmarks.

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CHAPTER V

ASTRONOMICAL MEANS OF AIR NAVIGATION

1. Astronomical Instruments and Procedures

Methods of Applying Them for Air Navigation

A basic astronomical aircraft instrument is the aircraft sextant, which makes it possible to measure angular distances between celestial bodies and the horizon, i.e., the so-called star altitude (see Section 4). If a navigator, using the sextant, measures the altitudes of two stars, he is able, upon processing the obtained data, to determine the locus of the airplane (MC). In daytime flights, when in the sky for the most part only the sun is visible (sometimes the moon), the navigator can, by measuring its altitude, plot on the chart the celestial position line (ALP) of the airplane – a straight line of equal altitudes or a geographic parallel. At the present time, thanks to the high quality of Soviet-produced aircraft sextants, the accuracy of in-flight measuring of stars altitudes reaches 3', which makes possible the plotting of the ALP with an error of about 7 km and the determining of the locus of the airplane with an error of about ±10 km.

Another astronomical aircraft instrument is the celestial compass, used in flight for solving two important problems: for determining the true course and for guiding the airplane along a set course. The Soviet-produced celestial compasses used in Soviet aviation make it possible to guide an airplane in the daytime along a set course with an accuracy of up 1 – 2°, which at any rate is not below the accuracy of guiding an airplane by magnetic compass.

Finally, a third astronomical aircraft instrument is the navigator's timepiece which must be of such high quality that the navigator (if he handles it properly) is able to determine by it the correct time, with an error not exceeding ±5 seconds.

The navigator processes star altitude data by means of an air almanac (calendar) and special, small tables. The in-flight calculations performed by the navigator with the help of the Astronomical almanac and tables are not complex but are arduous enough so that even a well-trained navigator has to spend 5 - 6 minutes on completing them. In cases of in-flight use of the celestial compass, the navigator likewise uses the air almanac for necessary calculations.

The astronomical aircraft aids to calculation include also the aircraft sidereal sky chart with the help of which the pilot can ascertain which of the stars will be visible at a particular time over the horizon and how they are situated relative to the horizon and sides of light.

The principal advantage of astronomical instruments is the complete independence of their application in flight from any connection with the ground. The navigator who is aloft in an airplane, during the performance of astronomical measurements and during their processing, has no need for radio communication nor for ground visibility. This obviates the fear that may be felt in the presence of artificially [sic] created disturbances, for example, the interferences during the use of radio means of aircraft guidance. There is only one "disturbance" which is to be feared by a navigator making celestial measurements - cloudiness, which might hinder his observations of celestial bodies.

Another advantage of astronomical instruments is the accuracy of astronomical determination regardless of the length and duration of the flight.

If a navigator knows how to determine the fix of the airplane on the basis of celestial measurements with accuracy within 10 km of his aerodrome, then so can he determine it with that same accuracy when located several thousand kilometers from the place of take-off. The accuracy of guiding an airplane by the celestial

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compass is just as independent from the distance between an airplane and its base.

A serious shortcoming of astronomical methods of airplane guidance is the length of the astronomical measurements and calculations made to determine the fix of the airplane. To the 5 – 6 minutes spent on calculations, it is necessary to add the no less than 3 minutes necessary for taking measurements of two star altitudes. However, while the outlay of 8 – 9 minutes on astronomical measurements and calculations is a bother to the navigator in an ordinary flight, in long-distance flight, when a route check need be made not oftener than once every half hour or even every hour, such an outlay of time on determining the fix of the airplane is fully permissible.

2. The Sidereal Sky

In order to use astronomical instruments successfully, the navigator of an airplane should know the sidereal sky well, and should be able to identify the most important constellations therein and also the so-called navigational stars, the astronomical coordinates of which (altitude and azimuth) are given in aircraft astronomical tables.

Constellations are groups of stars (or more precisely, sections of the sidereal sky) having more or less characteristic outlines, which were named by peoples of antiquity. For those, who are entering into the study of the sidereal sky for the first time, it is best of all for a good beginning to keep in mind the outlines of three constellations located in various, remote from each other, parts of the northern sky. The first of these constellations, called Ursa Major, has a form characteristic of a dipper formed by seven stars differing little from each other in brightness (see Appendix, "Sidereal Sky Chart"). The second constellation is Orion, in the central part of which are three fairly bright stars situated in a row very near each other, and the third constellation is Cygnus, having the shape of a cross, near which shines one of the brightest stars of the northern sky – Vega (belonging to the constellation Lyra).

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Stars usually are divided into stellar magnitude according to their brightness. The brightest of the stars are referred to as stars of zero magnitude, the less bright stars are stars of the first magnitude, the even less bright ones are stars of the second magnitude, etc. The faintest stars which can be still observed with naked eye are referred to as stars of the 6th magnitude. Stars of zero magnitude are on the average $2\frac{1}{2}$ times (approximately) brighter than stars of the first magnitude; stars of the first magnitude on the average are $2\frac{1}{2}$ times as bright as stars of the second magnitude, and so forth. The two most brilliant stars, Sirius and Canopus (the star Canopus is not visible in the USSR) are even considerably brighter than stars of zero magnitude; therefore, they are referred to as stars having a negative magnitude. In order that it would be possible with the help of these magnitudes to characterize more precisely the brightness of stars, the magnitudes of stars often are given not only in whole units, but also in tenths.

During his initial orientation in the sidereal sky, the navigator naturally comes to make use of the star chart and of these several constellations which he has already succeeded in memorizing. However, later on he must give up completely such a system of orientation, after having learned to identify the stars necessary to him, so to say "in person" by their color, brightness and also by the configuration of the neighboring groups of other stars.

Table I cites brief recommendations for identifying eighteen navigational stars. In the first column of the table are given two names of these stars, of which one, standing in brackets, indicates in what constellation it is situated and by what letter of the Greek alphabet it is denoted in this constellation.

Table I

Name of Star	Magnitude	Color	Method of Identification
Sirius (α Canis Majoris)	-1.6	white	By its brightness and by its position relative to the constellation Orion

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Name of Star	Magnitude	Color	Method of Identification
Vega (α Lyrae)	0.1	white	By its brightness. Situated near a small parallelogram of four weaker stars.
Capella (α Aurigae)	0.2	yellow	By its brightness. Forms a pentagon with three stars of the constellation Aurigae and one star of the constellation Taurus.
Arcturus (α Bootis)	0.2	orange	By its brightness. Lies at the continuation of Arc of the tail of Ursa Major constellation.
Rigel (β Orionis)	0.3	white	Found in the lower right corner of the constellation of Orion.
Procyon (α Canis Minoris)	0.5	white	By its position relative to the constellations of Orion and Gemini.
Altir (α Aguilae)	0.9	white	By the stars Vega and Deneb with which Altir forms an almost Isosceles triangle.
Betelgeuse (α Orionis)	0.9	red	By its light. Found in upper left corner of the constellation of Orion.
Aldebaran (α Tauri)	1.1	red	By its light. Near many small stars. Nearby are located the star cluster Pleiades.
Pollux (β Geminorium)	1.2	yellow	The brighter of two stars of the constellation Gemini; easy to identify by its appearance and by the constellation Orionis and Canis Minoris.
Spica (α Virgo)	1.2	white	Located at the top of an equilateral triangle formed by it, Arcturus and star β of Leo.
Antares (α Scorpii)	1.2	red	By its light and its position relative to the stars Vega and Arcturus.
Formalhaut (α Piscus Australis)	1.3	white	Located on the continuance of a straight line, passing through two stars of the right quadrant formed by Alpheratz and three stars of Pegasus.

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Name of Star	Magnitude	Color	Method of Identification
Deneb (α Cygni)	1.3	white	By the figure of the constellation of Cygnus having the form of a cross and by the stars Vega and Altir.
Regulus (α Leo)	1.3	white	Located in right lower corner of trapezoid formed by four stars of the constellation Leo.
Alioth (ε Ursa Majoris)	1.7	white	The brightest star of the constellation Ursa Major, third from the end of its handle.
Alpheratz (α Andromedes)	2.1	white	Located in the upper left corner of the quadrant formed by it and three stars of the constellation Pegasus.
Stella Polaris (α Ursa Majoris)	2.1	white	Located in extended straight line extending through the two extreme stars of the dipper formed by Ursa Major.

On a clear night it is not difficult to be convinced that all stars change their position relative to the sides of the earth, and relative to ground objects. A more careful study of this appearance indicates that during this the mutual position of the stars is not changed, so that the impression received is that all of the sidereal heavens is rotating, as a whole as if the stars were located on the inner part of a huge hollow ball (sphere). It is known that this apparent turning of the starry sky, proceeding from East to West (if you stand facing South) is an illusion actually produced by rotation of the Earth about its axis from West to East.

A considerable part of the stars, rise and set with the revolving sky, but there are also many stars which always remain visible above the horizon. Among the number of such stars in the middle northern latitudes are the stars of the Ursa Major, the bright star Capella and many others. It is most difficult of all to discover the shift of the Stella Polaris, which describes in the sky a small circle

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with an angular radius within one degree (which is approximately equal to twice the diameter of the moon). In the center of this circle is located a fixed point, called the North Celestial Pole, around which proceed the apparent rotation of the entire sidereal sky.

Besides the stars, in the rotating sky there are also found other celestial objects - the Moon and planets. The planets resemble the stars in appearance, however they not only travel like the stars around the pole of the world, but also shift comparatively quickly relative to the stars through the sidereal sky. This occurs because the planets are located hundreds of thousands of times closer to the earth than the nearest star and because they like the Earth itself revolve around the sun. For aircraft astronomical measurements it is possible to use only four of the brightest planets - Venus, Mars, Jupiter and Saturn. The brightness of Jupiter on the average surpasses several times the brightness of Sirius, the brightness of Saturn is near to the brightness of a star of the first magnitude, the brightness of Venus and Mars varies within great limits, it being known that the maximum brightness of Venus exceeds more than ten times the brightness of Sirius and the maximum brightness of Mars is near to the maximum brightness of Jupiter. For facilitating identification of the planets, the aircraft air almanac contains diagrams of their procession across the sky in the course of a year.

Even more noticeable than the procession of the planets, is the procession of the moon relative to the stars. This occurs because the moon actually moves around the Earth, circling the Earth once in 27.3 days. Thanks to this, the moon for that period of time proceeds through the sky and returns approximately to its previous location relative to the stars. During an hour the moon progresses along the sky by approximately the magnitude of its diameter.

It is much more difficult to realize that the sun also moves relative to the stars. Yet this is indicated by the change of altitude of the sun at noonday, proceeding with great predictability in the course of a year, and also by the circumstance, that on various days of the year night makes visible different stars. Thus, in the summer (in June) we cannot see the constellation Orion in the sky, since at the time the sun is situated near that constellation. Contrariwise, in winter (December) Orion is visible very well, whereas it is impossible to see the constellation Scorpion, near which the sun is situated at that time of the year. It is to be firmly remembered that the shifting of the sun relative to the stars is apparent and proceeds because the Earth moves around the sun, completing its path around it in one year.

3. Equatorial Coordinates

The airplane navigator during the making of astronomical measurements and calculations comes to deal with so-called astronomical coordinates, the determination of position of the stars in the celestial dome, similar to the geographic coordinates - latitude and longitude, determining the location of the various details of the earth's surface on the terrestrial sphere. We have seen above, that the resemblance of the sidereal sky to a spherical surface is a consequence of its mode of rotation, but it is also suggested by direct visual perception, since by day as well as by night, the dome of the sky reminds one of a hemisphere, resting along the horizontal edges of the earth. At the present time it is well known, that the sun, the moon, the planets and the stars are all located at very different distances from us. Nevertheless, it is regarded convenient to represent the sky in the form of a sphere enclosing the earth, on the inside surface of which all these celestial objects are situated. In particular, this makes it possible to use this imaginary celestial sphere for determining the location of the celestial objects by the same methods as those used for the determining location of details on the surface of the spherical earth.

Just as geographic coordinates are used for composing charts of the earth's surface, so with the help of celestial astronomical coordinates charts of the sidereal sky are composed. Here, necessarily, some of these lines which are repre-

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sented on the celestial sphere in the form of a circle, are depicted on the star charts as straight lines or curved lines other than circles. This must be remembered during the study of astronomical coordinates and during comparison of star charts with the sidereal sky.

Let us examine the star chart placed at the end of this book. In the center of the chart is found a fixed point, not taking part in the rotation of the stars of the sky – the North Pole of the universe. A number of circles, in the general center of which this point is located is called celestial parallels, and the straight lines spreading to various sides from the Pole are called circles of declination. The celestial parallel located at 90° from the Pole is called the celestial equator. It is evident that circles of declination on star charts correspond to terrestrial (geographic) meridians and celestial parallels correspond to terrestrial (geographic) parallels.

By using the straight lines and circles plotted on a star chart, it is possible to read the so-called equatorial coordinates depicted on the star chart – by their declination and direct ascension. On the celestial sphere these coordinates are segments of arcs of great circle of the celestial equator and circles of declination. They have much in common with geographic coordinates. Declination is reckoned by circles of declination on both sides from the celestial equator, from 0° to $+90^{\circ}$ on the side of the North Pole and from 0° to -90° on the opposite side. Right ascension is reckoned along the celestial equator from 0° to 360° (sometimes from 0 to 24 hours) from the so-called point of vernal equinox, across which the center of the sun passes on March 21. The apparent annual path of the sun relative to the stars is depicted on the chart in the form of a circle, the center of which does not coincide with the poles of the earth. This circle is called the ecliptic.*

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*On a celestial sphere the plane of the ecliptic inclines to the plane of the celestial equator at approximately 23°, 5'.

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It is easiest to understand the method of star chart reading, knowing that declination on the star chart is read just as latitude is read on terrestrial charts and direct ascension is read like longitude. Knowing this, it is possible, for example, to calculate on the terrestrial chart the declination of the star Vega (α Lyra) which equals approximately $+38^{\circ}$ and its right ascension which equals approximately 279° (the preciser values of equatorial coordinates of Vega are: $+38^{\circ}\ 44'$ and $278^{\circ}\ 50'$). Another example is the declination of the star Arcturus (α Bootis), as plotted on the star chart, equal approximately to $+20^{\circ}$, and its right ascension approximately equal to 213° (precise values of these coordinates: $+19^{\circ}26'$ and $213^{\circ}22'$). The declinations of stars and other celestial objects are denoted by the Greek letter δ and direct ascensions by the Greek letter α. The equatorial coordinates of stars change so very slowly, that for the purposes of airplane navigation it is possible to consider them constant for the course of a year. The equatorial coordinates of the sun and planets change much more quickly. Thus, the change of declination of the sun reaches $\pm 24'$ in a day and the change of its right ascension for a day amounts to $59'$. The equatorial coordinates of the moon change even much more quickly.

Neither the declinations nor the right ascensions of the stars are changed owing to the rotation of the sidereal sky. The declinations and right ascensions of the stars are changed mainly owing to the precession of the earth's axis, evidence of which is their slow shift in the sky at the Poles and points of vernal equinox. The principal cause of change in declination and right ascension of other heavenly bodies is found in their shift relative to stars, about which we spoke in Section 2. However, in practice we use another equatorial coordinate called the hour angle, which changes owing to the rotation of the sidereal sky, about which we will speak in more detail in Section 5.

4. Horizontal Coordinates

As we have seen, by using the declination and right ascension of stars, it is

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possible to compose a star chart, which can be used for a long time, since the equatorial coordinates of stars change extremely slowly and, especially, do not depend on changes in the position of an observer on the earth's surface. But it is just this valuable property of theirs that makes useless their measurement for deciding one of the basic problems of airplane navigation - determination of the fix of the airplane. For this purpose it is possible to employ the measurement of the so-called horizontal coordinates - the altitude and azimuth of the stars, quickly changing with the course of time both owing to the rotation of the starry sky and owing to a shift in an observer's position relative to the earth's surface.

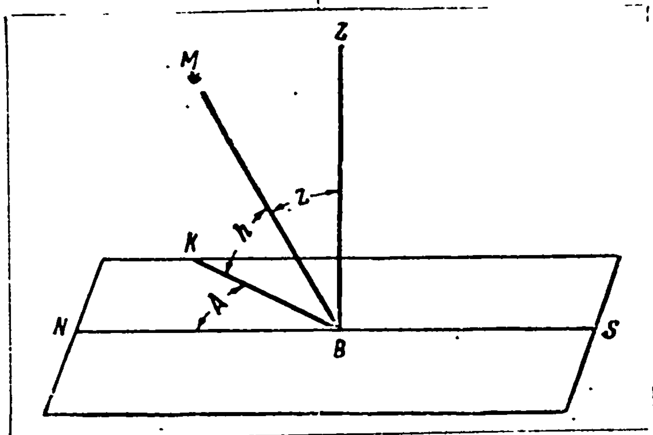

Fig.130 - Horizontal Coordinates

Figure 130 depicts a part of a horizontal plane, at one point of which - at point B - is located the observer. The line BZ, perpendicular to the horizontal plane is called the rhumb line (or vertical). It connects point B with point Z called the zenith. Line NS, lying on the horizontal plane, connects the northern point N with the southern point S. It indicates the direction of the meridian of point B and is called the midday line. At point M is located a star, rays from whose MB strike the eye of the observer. If through these rays and through the rhumb line BZ a vertical plane be plotted, it will intersect the horizontal plane along the line BK. Here the position of the star in the sky may be determined with the help of angle MBK between the horizontal plane and the direction to the star and the angle NBK between the direction to the northern point N and the line BK. The first of these angles is called star altitude and is denoted by the letter h, and the second is called star azimuth and is denoted by the letter A. If a star is located on the horizon, its altitude equals zero and if at its zenith, then the altitude is $+90^{\circ}$. The altitudes of stars situated below the horizon are calculated in the negative. Star azimuths are calculated from the northern point N in an eastward direction from 0° to 360°.

For deciding certain problems, instead of star altitude it is more convenient to use another coordinate termed zenith distance and denoted by the letter z. Zenith distance is related to the star altitude by the equation of $h + z = 90^{\circ}$, from which is evident that zenith distance is the complement of the altitude to 90°. In Fig.130 the zenith distance of the star z equals angle MBZ.

One great advantage of horizontal coordinates is the comparative simplicity of their measurement. Thus, star altitude can be measured by an apparatus of a comparatively simple design - the sextant, even in flight with a sufficiently high accuracy (3 - 4'). It is possible to measure the star azimuth to an accuracy of at least 1° by means of a deviational direction finder, if the magnetic declination of the place in which the measurement is made is known.

5. The Aircraft Star Chart and Calculations of Astronomical Coordinates on It

Besides the conventional star charts, like the one given in the supplement at the end of this book, the aircraft star chart BKN is also used in aviation astronomy. This chart is composed of three parts: the pedestal (foundation) made from thick cardboard, on which it is assembled; a rotating chart of the sidereal sky; and movable sheets with a notch depicting the horizon. The center of the revolving part of the chart (which is also the center of its rotation) coincides with the North Pole. Circles of declination are given only for four right ascensions — 0°, 90°, 180° and 270°. The only celestial parallel given is the celestial equator

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on which is plotted a scale of right ascensions through 10°. The scale of declination is plotted on two circles of declination also through 10°. Along the edges of the sliding part of the chart are plotted 365 divisions for the days of the year. These divisions are seen through a circular cut made in the removable sheet. Along this cut are plotted divisions of the hours at night time through every 10 minutes. On the edges of the oval cut in the movable sheet representing the horizon there are plotted graduation lines indicating the direction of north, south, east and west points and also - the azimuth scale through each 30°.

By rotating the mobile part of the chart, it is possible to combine division of a given day of the year with division of a given hour. After this in the notch of the movable sheet of the chart there will be seen a picture of the sidereal sky corresponding to the given moment of local civil time.

Here it is to be kept in mind that local civil time, denoted by T_M, can be obtained from the zone time T_p by the following formula

$$T_{\text{м}} = T_p - (N - \lambda), \qquad (1)$$

where λ = longitude of locus

N = number of the hour zone according to which time the timepiece of the navigator is set.

For example, the navigator's timepiece is set for the third time zone (i.e., N = 3), longitude of locus (East) λ = 2 hrs. 33 min.; and time zone T_p = 18 hrs. 15 min. It is necessary to find local civil time T_M.

Solution: T_M = 18 hrs. 15 min. - (3 hrs. - 2 hrs. 33 min.) = 18 hrs. 15 min. - 27 min. = 17 hrs. 48 min.

If the positions of the moon and planets (see Section 6) are previously plotted on the BKN according to the data of the air almanac, then after appropriate adjustment of the mobile part of the chart it is possible to obtain a clear representation of the disposition of these stars on a given day and hour both relative

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to the stars and relative to the horizon and the four cardinal points.

In addition to its basic purpose — to indicate a chart of the starry sky at a given moment, the BKN can serve also for better comprehension and approximate reading of the equatorial and horizontal coordinates.

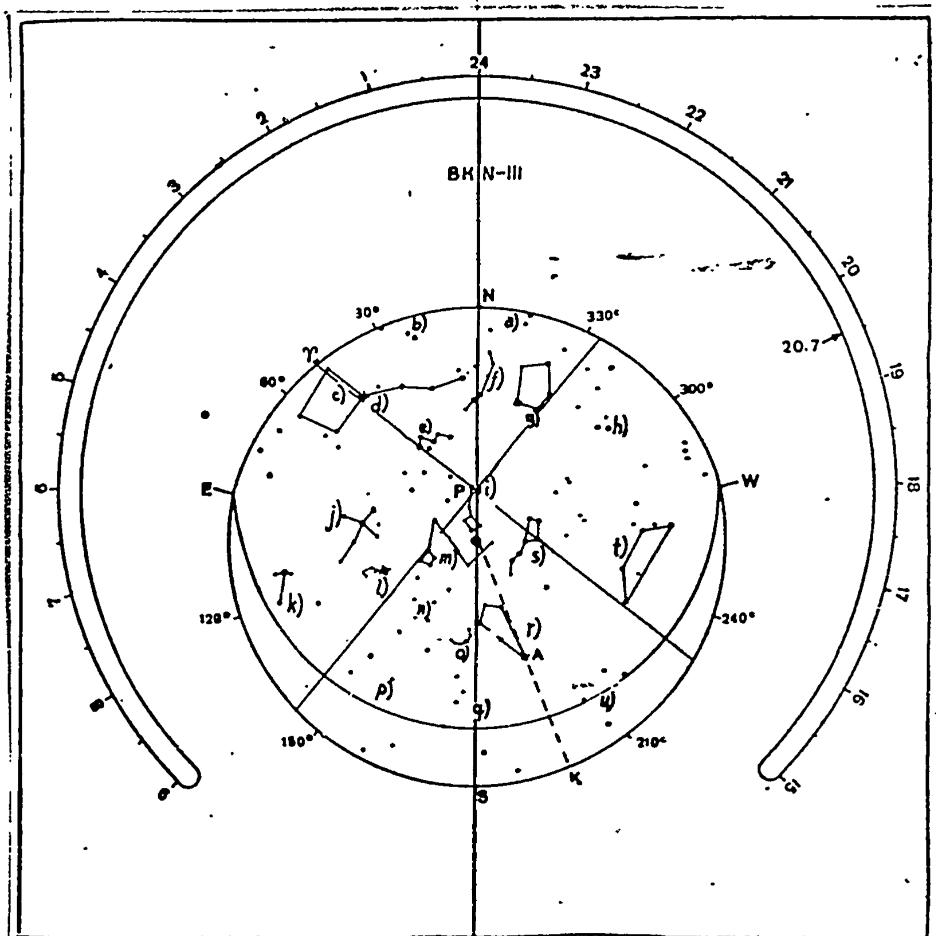

Fig.131 – Calculations of Star Altitudes and Azimuths on a Mobile Star Chart

a) Aries; b) Owen; c) Pegasus; d) Cassiopeia; e) Andromeda; f) Perseus; g) Auriga ; h) Gemini; i) Ursa Minor; j) Cygnus; k) Aguila; l) Lyra; m) Draco; n) Hercules; o) Corona Borealis; p) Serpens ; q) Scorpio; r) Bootis; s) Ursa Major; t) Leo; u) Virgo

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In order to plot the readings of the coordinates of stars more easily and graphically on the BKN it is recommended to take a cord with a knot tied in it and to stretch it across the chart so that it passes between North and South points. The knot of the cord must be placed in the oval notch of the horizon, whereupon it will be the approximate indication on the chart of the location of the zenith Z. The line, along which the cord passes on the star chart will represent the so-called celestial meridian, the plane of which coincides with the plane of the terrestial meridian. Beside passing through the points N, S, and Z, the celestial meridian passes also through the center of rotation of the chart, that is through the North Pole, denoted by the letter P (Fig.131).

Bring the star chart into the position at which the 20 July calibration (on its mobile part) coincides with the calibration of 19 hrs.30 min. (on the removable leaf). Having glanced at the chart, we see that the Ursa Major constellation is situated not far from the zenith, in the southwest direction from it; the constellation of Cygnus is situated above the East point, and the constellation Bootis is in the southern part of the sky, etc. In order to calculate on the chart the horizontal coordinates of any star, for example, Arcturus (α Bootis), we proceed as follows: Take a second cord and stretch it across the chart so it passes through the zenith Z and Arcturus A (see the dotted line ZAK in Fig.131). Thus the string forms a so-called vertical circle of the star (or vertical) that is a circle passing through the star and the zenith in the celestial dome.

Point K situated on the horizon has obviously an altitude equal to zero and point Z has an altitude equal to 90°. Knowing this, it is possible to calculate by eye that Arcturus (point A) has an altitude equal to approximately 45°. At the same time from the location of point K on the horizon it is possible to obtain the approximate magnitude of the azimuth of Arcturus, nearly 195°.

This method of determining the horizontal coordinates may be used for determining the altitude of the celestial pole, and in this case it is not necessary to

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use the second cord since the poles of the earth are situated on a celestial meridian which is its vertical. The value of the altitude of the celestial pole is very great since it equals the latitude of the locus. It is possible to observe by eye that in Fig.131 the altitude of the pole is approximately 70°; the magnitude of that latitude, for which the notch of the horizon of the BKN was set as depicted in this illustration.

Naturally, one and the same BKN may wholly satisfactorily furnish a star chart of the sky at a given time also in the event when the latitude of the locus of the observation differs somewhat from the latitude for which the notch of the BKH horizon is set. In connection with this, three different aircraft star charts are used in Soviet aviation; BKN-1, the horizontal notch of which is set for north latitude 37°, BKN-11 with the horizontal notch for latitude of 53°; and BKN-111 with horizontal notch for 69° latitude. It is assumed that BKN-1 will be used in latitudes from 30° to 44°; BKN-11 in latitudes from 46° to 60°; and BKN-111 in latitudes from 62° to 76°. In Figs.131 and 132 a BKN-111 is shown.

In order to make on the BKN an approximate reading of the equatorial coordinates of some star, the second cord must be stretched somewhat differently so that it passes through the star and the celestial pole. Set the star chart in a position at which the division March I (on its movable part) coincides with the division of 2100 hours (on the movable sheet) and stretch the second cord across the pole P and the star Capella K (see the dotted line in Fig.132). This string depicts the declination circle of the star Capella, intersecting the celestial equator at point L. Since the declination of point L equals zero and the declination of the pole P equals 90°, it is possible to determine by eye (or by using the divisions printed on the circles of declination) that the declination of Capella is somewhat less than 50°. The right ascension of Capella can be determined by using the divisions on the celestial equator according to the position occupied there by point L; as is seen in Fig.132, it is somewhat less than 80°.

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Using Fig.132, it is possible to explain what is represented by the third equatorial coordinate which we already mentioned in Section 3 - the hour angle. At the

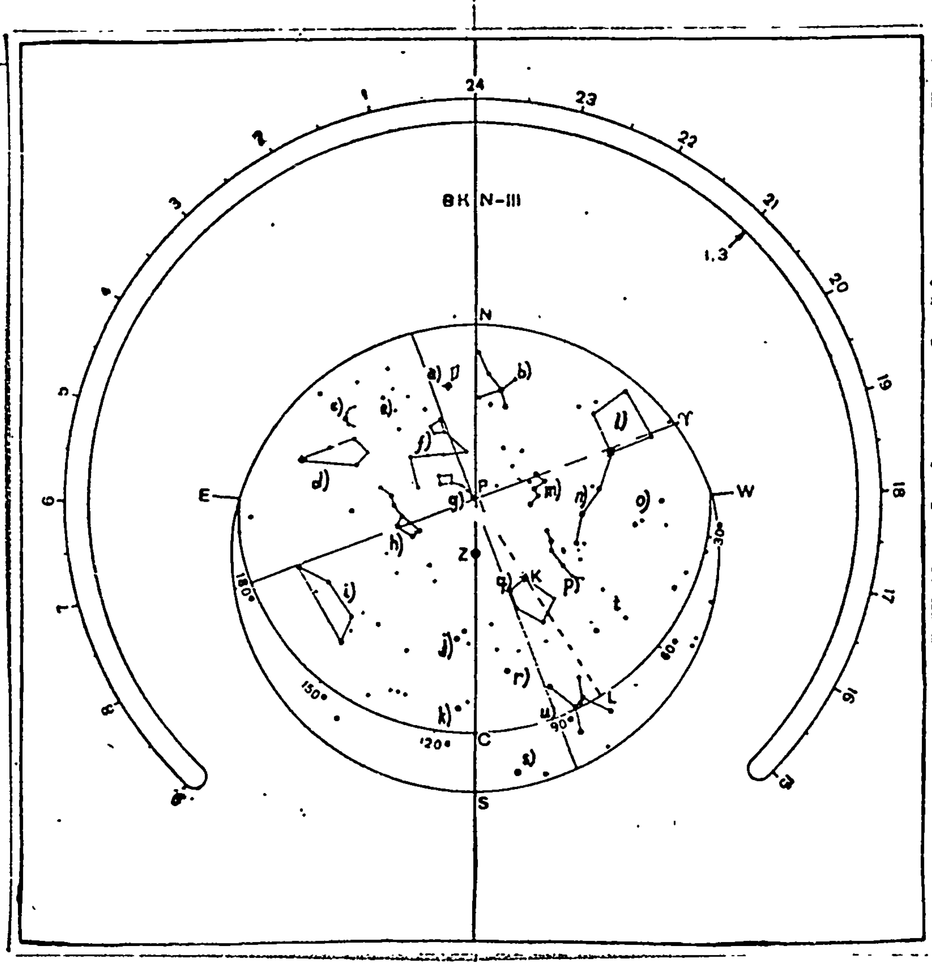

Fig.132 - Calculation of Equatorial Coordinates of a Star on a Moving Star Chart

a) Lyra; b) Cygnus; c) Corona Borealis; d) Bootis; e) Hercules; f) Draco; g) Ursa Minor; h) Ursa Major; i) Leo; j) Gemini; k) Canis Minor; l) Pegasus; m) Cassiopeia; n) Andromeda; o) Owen; p) Perseus; q) Auriga ; r) Taurus; s) Canis Major; t) Aries; u) Orion

moment when a star passes through the southern part of the celestial meridian (between the pole P and the South point S), and when its circle of declination coin-

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cides with the celestial meridian, the hour angle of this star equals zero. Subsequently, owing to the rotation of the sidereal sky, the star will move in a westward direction from the celestial meridian and its hour angle will be equal to the angle between its circle of declination and the southern part of the celestial meridian. In Fig.132 the hour angle of Capella equals the angle CPL, i.e., approximately 30°. Since the sidereal sky is rotating uniformly, the hour angles of the stars change uniformly in strict proportion to the time. The hour angle is denoted by the letter L.

The hour angles of celestial objects, calculated in a western direction from the southern part of the celestial meridian are called western hour angles. The western hour angle is computed from zero to 360°. However in certain cases the eastern hour angle is also used, as computed to the east from the southern part of the sky meridian from 0° to 180°. It is not difficult to ascertain that between the western and eastern hour angles there exist the following simple relationship:

$$t_E = 360^\circ - t_W, \tag{2}$$

where t_E = eastern hour angle

t_W = western hour angle of the same star.

The western hour angle of the point of vernal equinox, which is called sidereal time, has great significance in astronomy and is denoted by the letter S. At that moment when the point of vernal equinox intersects the southern part of the celestial meridian, sidereal time equals zero. On various days of the year this occurs at various times of the day. Thus, at the end of March this occurs near midday, at the end of June near six a.m., at the end of September near midnight, and at the end of December near 6 p.m. Therefore, sidereal time is inconvenient for use in everyday life. Sidereal time changes from 0° to 360° (or from zero to 24 hours) in the course of a period of time termed sidereal day. A sidereal day is almost four minutes shorter than the solar day, which we use in practical life.

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In Fig.132, the declination circle passing through the point of vernal equinox is denoted by $P\gamma$ (the sign γ usually denotes the point of vernal equinox). Because of this the hour angle of the point of vernal equinox (i.e., sidereal time S) equals the angle $CP\gamma$. But from the illustration it is seen that $\angle CP\gamma = \angle CPL + \angle LP\gamma$, and since $\angle CPL$ equals the western hour angle of Capella t, and $\angle LP\gamma$ equals the right ascension of Capella α then it is obvious that

$$S = t + \alpha. \qquad (3)$$

In Fig.132, sidereal time S equals approximately 110° and in Fig.131 approximately 230° (see the location of the declination circle $P\gamma$ in that illustration). This means, that for any star in the former case the sum of its western hour angle and right ascension equals 110° and in the latter case, 230°.

By using the BKN, it is possible to solve (approximately) various secondary astronomical problems for example, to determine the moment of rising and setting of various stars on a given day of the year or the moment of passage of stars through the southern or northern part of the celestial meridian. For determining the moment of rising or setting of any star, it is necessary, by rotating the movable part of the chart, to place this star in the eastern or western part of the horizon, and then observe, at what moment, expressed in hours and minutes, it meets with a given calibration. It is only to be remembered that the time obtained refers to local civil time which has to be converted to its time zone by using eq.(1) (see Section 6).

The passages of stars across the celestial meridian are of special interest, since at the moments of these passages the star altitudes reach their greatest or smallest values, depending on whether the stars pass across the southern or the northern part of the celestial meridian. In this connection, the passage of the star in the southern part of the meridian (between points P and S in Fig.131 and 132) is called the upper culmination of the star and the passage of stars in the

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northern part of the celestial meridian (in a northward direction from point P) is called the lower culmination of the star. For determining the moment of upper or lower culmination of any star it is necessary, by rotating the movable part of the chart, to place the star in the southern or in the northern part of the celestial meridian and to read the moment of local civil time, corresponding to the number set.

At the moments of upper and lower culmination of the star (or any other star) its altitude is linked by a direct relationship to its declination and the latitude of locus:

a) At the upper culmination of the star between the zenith Z and South point S:

$$h = 90^\circ - \varphi + \delta; \qquad (4)$$

b) At the lower culmination of the star between the pole P and the zenith Z:

$$h = 90^\circ - \delta + \varphi.$$

Since at the moment of upper culmination of a star its western hour angle equals zero and at the moment of lower culmination this angle equals 180°, then from eq.(3) it follows that at the upper culmination of a star its right ascension equals sidereal time, i.e., $S = \alpha$ and at its lower culmination the right ascension of the star differs from sidereal time by 180°, that is $S = \alpha \pm 180^\circ$.

6. Solar Time

In the preceding section we indicated that sidereal time is impractical for use in everyday life, because the beginning of a sidereal day (the moment of upper culmination of the point of vernal equinox) in the course of a year occurs at different times of the day and night.

This shortcoming is not displayed by solar time, which is used in various forms, but most often in the form of so-called zone time.

It would seem that it would be most rational to use the hour angle of the

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center of the sun for measuring solar time.

However this time, called true solar time, is unhandy because it is based on a unit - a true 24-hour day - equaling the time interval between two consecutive upper culminations of the center of the sun, which changes somewhat in the course of a year.* Therefore in practice there usually is used an apparent solar time differing somewhat from the true such time, with units that are strictly constant. This apparent solar time is based on the use of a special fictictious (imaginary) point called mean sun.

It is assumed that the mean sun moves uniformly along the celestial equator in the same direction in which the true sun moves along the ecliptic. Here, the mean sun is chosen so that its right ascension differs from the right ascension of the center of the sun by not more than $4^{\circ}.1$. The time measured by the western hour angle of the mean sun is called mean time. The mean day, the duration of which is strictly constant and which equals the interval of time between two successive (Identical) culminations of mean sun, is used as the basic unit of mean time. The mean day is divided into mean hours, minutes and seconds. These are the same units of time which are used in everyday life, in mechanics and in physics.

The mean day begins at the moment of upper culmination of the mean sun, that occurs approximately in the middle of the day (at mean midday). Obviously, this creates great inconvenience in the counting of days, in consequence of which, everyday life has long been based on the so-called civil time which differs from the mean time by 12 hours and is calculated from the moment of lower culmination of the mean sun (from the moment of mean midnight).

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*The changing duration of a true solar day is caused by two reasons: first, the sun moves unevenly along the ecliptic, second, the ecliptic slants to the celestial equator, due to the fact that the identical passages of the sun along the ecliptic correspond to its unidentical passages along the celestial equator.

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In USSR civil time was used until June 1919, when by a decree of the government it was replaced by more convenient zone time. The reason for this change is as follows:

Civil time is measured by the western hour angle of the mean sun, increased or decreased by 12 hours. Therefore civil time at one geographical meridian differs from civil time at any other meridian. It becomes the greater the more eastward is the position of the meridian passing across the locus of the observer, i.e., the greater is the longitude of that locus. Therefore, civil time is also called local civil time, since it varies with the longitude of the location. Between local civil time and the longitude there is the following relationship:

$$\lambda_2 - \lambda_1 = T_{M_2} - T_{M_1}, \tag{5}$$

where λ_1 and λ_2 are longitudes of two meridians;

T_{M_1} and T_{M_2} are the local civil times corresponding to these longitudes.

Equation (5) is stated thus: the difference in longitudes equals the difference in local civil times.

Thus, any relatively small change in the longitude of an observer, moving along the earth's surface is accompanied by a corresponding change in local civil time. Because of this it is easily possible for confusion to arise, especially in railroad, telegraph and telephone traffic. In this connection, in the USSR and in most other countries, local civil time has been replaced by zone time.

The reforms accompanying the introduction of time zones included the following: the entire terrestrial sphere was divided into 24 hour zones by meridians, situated at 15° longitude apart from each other, or, which is the same thing, one hour apart. Each zone received its own number - zero, 1, 2, etc. up to 23. The zero zone was chosen so that its center would be passed by the Greenwich meridian from which, as is known, calculations of longitude are made.

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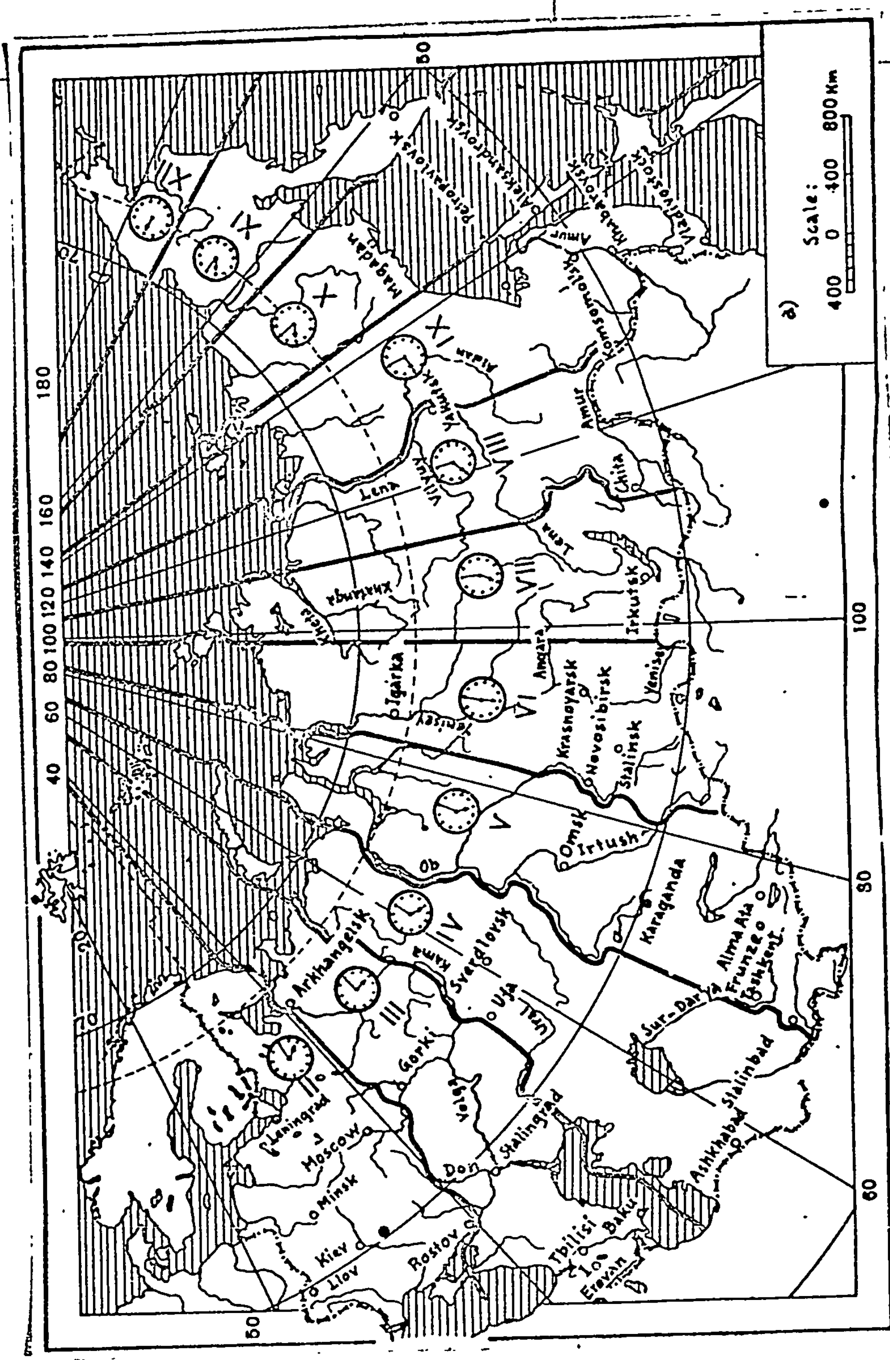

Fig.133 - Chart of Time Zones

a) Chart of time zones Scale

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The zone numbers increase in an eastward direction that is the mean meridian of the first zone has an east longitude of 1 hour, the mean meridian of the second zone has an east longitude of two hours, etc. The time within each zone is considered to be uniform - along the longitude of the mean meridian; in the zero zone - it is Greenwich local civil time, in first meridian zone - it is one hour ahead, in the second zone it is two hours ahead, etc. So, throughout the earth, instead of an endless multiplicity of various local times, there are altogether only 24 times differing from each other by whole hours. In order to know the difference in the zone times of two zones, it is necessary to subtract from the number of one zone the number of the other

$$T_{p_2} - T_{p_1} = N_2 - N_1. \qquad (6)$$

For example, the difference in time between the tenth zone and the third zone equals seven hours.

Greenwich local time, i.e., the time of the zero zone is denoted by T_{gr}, and is usually called simply Greenwich time. It plays an important role, because the coordinates of stars and other data in air almanacs are given in Greenwich time. Since Greenwich time corresponds to a zero zone number, it follows from eq.(6) that

$$T_{gr} = T_p - N. \qquad (7)$$

The width of each zone in longitude equals 1 hour, therefore the zone boundaries differ by half an hour from mean meridians and the local time of the boundaries of a zone should likewise differ by half an hour from the zone time of the zone. In reality, however, the matter is not quite like this because the boundaries of hour zones usually pass not along the meridians but along state and administrative frontiers, along great rivers, etc. Therefore, the difference between zone and local civil time may sometimes exceed half an hour. For determining this difference it is possible to use eq.(6). Since the zone time is the local time of

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the mean meridian of a zone the longitude of which equals the number of the zone N, then

$$T_p - T_{\text{м}} = N - \lambda. \qquad (8)$$

By using eq.(8) it is possible to make the conversion from local civil time to zone time and the opposite. In the USSR in the summer of 1930 all times established by the government were moved ahead one hour. Due to this we live not in that time zone in which we were placed by the introduction of zone time but in the time zone of adjacent eastern zone. Thus, for example, Moscow is located in the second zone, but the so-called Moscow time is the time in the third time zone.

The transfer to one hour ahead of the zone time in the USSR is usually termed decretal time. The difference between the decretal zone time and local civil time can be found by eq.(8), with the stipulation that the number of the zone is not only taken from the table or from charts of the time zones (drawing 133) but also is increased by one hour.

Thanks to decretal time in the USSR the difference between the zone (decretal) time and local civil time is always positive.*

In consequence of the huge extent of the Soviet territories in longitude, there are eleven time zones in USSR, from the third to the thirteenth zone.

7. The Air Almanac

As noted before (Section 1) the navigator conducts astronomical calculations in flight with the aid of the air almanac and special tables. The air almanac (abbreviated AAE), i.e., an astronomical almanac for the purposes of air navigation, has been issued in the USSR since 1930, much earlier than in most other countries. It is published once annually. Each day of the year is corresponded by

*Exclusive of the Tartar Autonomous SSR, which is situated in the third hour zone and uses the time of that time zone.

Table 2

INTERPOLATION TABLES

Sun, Planets, Stars

M	° ′	M	° ′
0	0 00	30	7 30
1	0 15	31	7 45
2	0 30	32	8 00
3	0 45	33	8 15
4	1 00	34	8 30
5	1 15	35	8 45
6	1 30	36	9 00
7	1 45	37	9 15
8	2 00	38	9 30
9	2 15	39	9 45
10	2 30	40	10 00
11	2 45	41	10 15
12	3 00	42	10 30
13	3 15	43	10 45
14	3 30	44	11 00
15	3 45	45	11 15
16	4 00	46	11 30
17	4 15	47	11 45
18	4 30	48	12 00
19	4 45	49	12 15
20	5 00	50	12 30
21	5 15	51	12 45
22	5 30	52	13 00
23	5 45	53	13 15
24	6 00	54	13 30
25	6 15	55	13 45
26	6 30	56	14 00
27	6 45	57	14 15
28	7 00	58	14 30
29	7 15	59	14 45
30	7 30	60	15 00

Moon

M	° ′
0	0 00
1	0 14
2	0 29
3	0 43
4	0 58
5	1 12
6	1 27
7	1 41
8	1 56
9	2 10
10	2 25

All Heavenly Bodies

c	′
0	0
4	1
8	2
12	3
16	4
20	5
24	6
28	7
32	8
36	9
40	10
44	11
48	12
52	13
56	14
60	15

a page of the almanac, where the declination and Greenwich hour angles of the sun and of three planets, and also the Greenwich sidereal time, are given for each hour of the Greenwich time T_{gr} of the day. For the moon, the equatorial coordinates of which change much more quickly and unevenly, the declinations and hour angles are given for every ten minutes of Greenwich time. Besides this, each page of the AAE contains tables of corrections entered into measurements of the altitude of the moon owing to lunar parallax (see Section 13). The AAE is complemented with an insert containing the values of declinations and right ascensions of 30 stars. On the reverse side of the insert, just as on the reverse side of the title page of the almanac, there are interpolation tables, serving for introduction of corrections for Greenwich time minutes and seconds into sidereal hour angles and into sidereal time (see Table 2). At the end of the almanac there are diagrams of the passage of the planets across the sky in the course of a year.

Besides this, the AAE is provided with an appendix, "Tables of Moonrise, Moonset, and Moon Phases".

The basic problem to be resolved with the help of AAE, consists in computing the sidereal hour angles and declinations and also sidereal time for a given moment of a time zone. Since in the AAE all coordinates of stars are given for Greenwich time only, it is necessary to convert a given zone time to Greenwich time by eq.(7).

The declination of stars selected from the AAE for the obtained Greenwich time can serve in the processing of astronomical measurements conducted in any location on the earth's surface. The matters stand otherwise with the sidereal hour angles and sidereal time taken from the AAE, since the values of these coordinates in the almanac are given for the Greenwich meridian. In order to convert the Greenwich hour angle t_{gr} and Greenwich sidereal time S_{gr} to hour angle t and to sidereal time S corresponding to longitude λ at which the navigator is located at the moment of making astronomical measurements it is necessary to use one of the following

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formulae:

$$t=t\ +\lambda; \qquad (9)$$

$$S=S\ +\lambda. \qquad (10)$$

In these formulae eastern longitude is considered positive and the western, negative.

Let us illustrate the procedure for computing sidereal hour angles and sidereal time by the following examples:

<u>Example 1</u>. Find: the sidereal time for the instant of 5 hrs. 14 min. Moscow time (i.e., time of third time zone) on August 8, 1952, if the eastern longitude of location is $\lambda = 38°16'$.

a) From eq.(7) calculate T_{gr} = 5 hrs. 14 min. – 3 hrs. = 2 hrs. 14 min.

b) From the 1952 AAE select S_{gr} for the moment T_{gr} = 2 hrs.; we obtain $S_{gr} = 346°32'$.

c) To the obtained S_{gr} add the correction for 14 min.; taken from the interpolation tables (see Table 2). This correction equals $3°30'$. Ultimately we obtain:

$$S_{gr} = 346°32' + 3°30' = 350°02'.$$

d) Calculate from eq.(10) the sidereal time corresponding to the given longitude of location

$$S = 350°02' + 38°16' = 388°18' = 28°18'$$

<u>Note</u> – In those cases when the sum of the angles is obtained greater than 360°, it is necessary to subtract 360° from it.

<u>Example 2</u>. Find: the declination and hour angle of the sun for the instant of 10 hrs. 37 min. 20 sec. Moscow time, October 27, 1952, if the eastern longitude of location is $\lambda = 41°43'$.

a) From eq.(7) calculate t_{gr} = 10 hrs. 37 min. 20 sec. – 3 hrs. = 7 hrs. 37 min. 20 sec.

b) From the 1952 AAE select for the obtained T_{gr} the declination of the sun $\delta = -13^\circ + 13'$ (Section 8 provides the explanation why the degrees and minutes of declination in the AAE have independent signs).

c) From the AAE we take the t_{gr} of the sun for the instant of $T_{gr} = 7$ hrs; we obtain $t_{gr} = 289^\circ 01'$.

d) To the obtained t_{gr} we add the correction for 37 min. 20 sec. taken from the interpolation tables, this correction equals $9^\circ 20'$. We obtain ultimately

$$t_{gr} = 289^\circ 01' + 9^\circ 20' = 298^\circ 21'.$$

e) Calculate from eq.(9) the hour angle of the sun corresponding to the given longitude of location:

$$t = 289^\circ 21' + 41^\circ 43' = 331^\circ 04'.$$

Hereafter we will call the sidereal hour angles and sidereal time corresponding to longitude other than zero by the appellations of the local hour angle of a star and the local sidereal time. Thus in example 1 the local sidereal time was found for the instant given, and in example 2 the declination of the sun and its local hour angle were determined.

With the aid of the AAE it is also possible to solve reverse problems consisting in the calculation of the instant corresponding to a given hour angle of a star or to a given sidereal time. The procedure for the solution of such a problem is illustrated by this example:

Example 3. Find: the instant in the fifth time zone on 16 December 1952, at which the local hour angle of the planet Mars equals 30°; eastern longitude of location $\lambda = 61^\circ 28'$.

a) From a modified eq.(9) we find the Greenwich hour angle of Mars, $t_{gr} = 30^\circ - 61^\circ 28' = -31^\circ 28' = 328^\circ 32'$.

b) On using the 1952 AAE, we ascertain that at the moment $T_{gr} = 13$ hrs., the Greenwich hour angle of Mars equals $318^\circ 21'$.

c) We calculate the difference between the calculated t_{gr} of Mars and the T_{gr}

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of Mars (for 13 hrs.) taken from the AAE

$$328^\circ 32' - 318^\circ 21' = 10^\circ 11'.$$

d) With the aid of the interpolation tables we ascertain that the sidereal hour angles change by $10^\circ 11'$ for 40 min. 44 sec. This means that the Greenwich hour angle of Mars will equal $328^\circ 32'$ following 40 min. 44 sec. after $T_{gr} = 13$ hours.

e) We calculate the instant in Greenwich time:

$$T_{gr} = 13 \text{ hrs. } 40 \text{ m. } 44 \text{ sec.}$$

f) We calculate the instant in the fifth time zone, using the modified eq.(5):

$$T_p = 13 \text{ hrs. } 40 \text{ m. } 44 \text{ sec.} + 5 \text{ hrs.} = 18 \text{ hrs. } 40 \text{ m. } 44 \text{ sec.}$$

By an analogous method it is possible to find the instant in zone time if the local sidereal time is given instead of the local sidereal hour angle star (as in example 3).

If it is necessary to calculate with the aid of the AAE the hour angle of some star for a given instant, the calculation has to be begun by determining the sidereal time for that instant (as in example 1) and thereupon in accordance with eq.(3), on computing the right ascension of the star from that sidereal time, the star's hour angle is obtained. Thus, if the procedure in example 2 be used to find the hour angle of Aldebaran (α Aries), the right ascension of which equals $68^\circ 17'$ then the calculation of this hour angle would be thus shortened:

$$t = S - \alpha = 28^\circ 18' - 68^\circ 17' = -39^\circ 59' = 320^\circ 01'.$$

It is to be noted that the finally obtained hour angle $320^\circ 01'$ is western hour angle of Aldebaran while as the hour angle $39^\circ 59'$, obtained with a minus sign, is its eastern hour angle. It is not difficult to see that these hour angle values satisfy eq.(2).

As noted before, the AAE contains diagrams of the passage of the planets through the sidereal sky during the course of the year. To find the planets in the sidereal sky, these diagrams can be used either directly or indirectly by plotting their planet position data on the BKN. For plotting the position of the moon on

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the BKN it is necessary to take its declination from the AAE and to calculate its right ascension by the modified eq.(3)

$$\alpha = S_{gr} - t_{gr}$$

where the Greenwich sidereal time S_{gr} and the Greenwich hour angle of the moon t_{gr} for a given day and hour are taken from the AAE.

8. Altitude and Azimuth Tables

The first aircraft astronomical tables used in our aviation, a publication of the Air Fleet in 1916, were drawn up by N.Kalitin. They made it possible to calculate, on the basis of altitude measurements of two stars - Polaris and a western or eastern star - the latitude of location and local sidereal time. Longitude was determined by a modified eq.(10). The endeavors to simplify and shorten astronomical calculations in flight led to their significant changes. Original and ingenious methods of longitude calculation were introduced by A.N.Volokhov who compiled in 1928 the so-called "Graphs of the Longitudes of Stars" which in conjunction with the determination of the latitude from the Polaris were used to solve problems of controlling the course with the aid of astronomical methods of air navigation. Volokhov's graphs were used for several years in Soviet aviation and, doubtless, were the prototype (first form) of the astrographs of the American navigator Weems, who used in his "invention" the idea of Volokhov's graphs (which was, of course, not mentioned by Weems).

In the period of preparation for the historic transarctic flights of 1936-1937 the P.K.Shternberg Moscow State Astronomical Institute compiled tables of star altitudes which were the first version of the contemporary altitude and azimuth tables worked out by L.P.Sergeyev. These latter tables were published in 1941 but already in 1939-40 they were printed by photographic means and used in our aviation. It is curious to note that astronomical aviation tables published in England in 1941 showed such resemblance to Sergeyev's tables, that there can be no doubt as

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to their plagiarism.

The subsequent editions of altitude and azimuth tables of the sun, moon and planets (abbreviated TVA) developed by L.P.Sergeyev were published (in 1946 and in the following years) in five books for the northern latitudes from 14° to 28° (TVA-Yu) from 30° to 44° (TVA-1) from 46° to 60° (TVA-2) from 62° to 76° (TVA-3) and from 78° to 88° (TVA-4). Somewhat later there was published a supplementary TVA-1c for northern latitude from 28° to 54° and a TVA-2c for northern latitudes from 52° to 78°.

In the TVA the altitudes and azimuths of solar-system bodies are given for declinations expressed in whole degrees from 0 to ±29°, for degrees of latitude expressed in even numbers and for degrees of hour angles expressed in even numbers.

In table 3 (see p. 111) are presented part of one of the even-numbered pages of TVA-2 and of one of the odd-numbered. Its columns represent latitudes 46°, 48°, 50° and 52°. Positive declination is indicated in the upper part of the table (+15°) and negative (-15°) in the lower part of the odd page. The hour angle t is given in the first column to the left, and on odd pages - also in the first column to the right. The value of altitude h in the table is given with an accuracy to 1', the value of the azimuth A - an accuracy of 1°. In order that the table's altitude values can be corrected to minutes of declination, an index f is given in the tables. Corrections for minutes of declination are taken from the index and for the number of minutes of declination from an auxiliary table compiled for minutes of declination from 0' to 30'.

Therefore in the AAE the star declinations are given in special transcript: the degrees and minutes of declination have independent signs. If the number of minutes of declination is positive, the correction of the tabulated star altitude is entered with a plus sign, and if the number of minutes of declination is negative the correction has a minus sign. This rule retains its validity independently of what sign stands before the degrees of declination; plus or minus. On the odd-numbered pages of the TVA the boundaries between the altitude and azimuth values pertaining to the positive and negative declination are denoted by a broken (horizontal) line.

Since in the TVA the star altitude and azimuth values are given for hour angles not exceeding 180°, in cases when the western hour angle of a star proves to be greater than 180°, it has to be converted as per eq.(2) into eastern hour angle. Thus, for example, in the solving of example 2 there was obtained a western hour angle of the sun 331°04' W, in order to use the TVA to find the altitude and azimuth of the sun according to this hour angle, it is necessary to find the corresponding eastern hour angle of the sun which equals $360^\circ - 331^\circ04' = 28^\circ56'$ E.

If a solar-system body has an eastern hour angle then it is located in the eastern part of the sky and its azimuth does not exceed 180°. In this case, the tabulated TVA azimuth is the navigational (north-eastern) azimuth. If a solar system body has a western hour angle its navigational azimuth must be greater than 180° and for obtaining this azimuth by means of the TVA it is necessary to take the complementation of this azimuth to 360°. This will be illustrated in the examples below. The procedure for doing this in flight will be explained in Section 14.

In solving the examples of the use of the TVA we will use hour angles that are always expressed in an even number of degrees.

Example 4. Declination of solar-system body $\delta = +15^\circ + 23'$, hour angle of solar-system body $t = 26^\circ$E. latitude of location $\varphi = 48^\circ$. Find from the TVA the altitude and azimuth of the solar-system body.

From table 3 we find: altitude of solar-system body $h = 50^\circ39' + 21' = 51^\circ00'$ navigational azimuth $A = 138^\circ$.

Example 5. Declination of solar-system body $\delta = +15^\circ - 16'$, hour angle of solar-system body $t = 14^\circ$W. latitude of fix $\varphi = 52^\circ$. Find from the TVA the altitude and azimuth of the star.

From table 3 we find

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– altitude of solar-system body $h = 51°21' - 16' = 51°05'$;

– navigational azimuth $A = 360° - 158° = 202°$.

Example 6. Declination of solar-system body $\delta = -15° + 09'$; hour angle of star $t = 62°E$. latitude of fix $\varphi = 46°$. Find from the TVA the altitude and azimuth of the star.

From table 3 we find

– altitude of star $h = 7°24' + 7' = 7°31'$;

– navigational azimuth $A = 121°$.

Other tables published in 1946 are employed for calculating the altitudes and azimuths of stars. These tables of star altitudes and azimuths (abbreviated TVAZ) were compiled for the same intervals of latitude as the TVA. In the TVAZ for the even values of latitude for each degree of sidereal time are corresponded by the altitude values (to an accuracy of 1') and the navigational azimuths (to an accuracy of 1°) of four or five navigation stars from the number listed in Table I, and also the difference between the latitude of the location and the altitude of the Pole star (in the tables these differences are called corrections in the altitude of the Pole Star).

A part of a page of TVA-3 is given in table 4.

No corrections for the tabulated altitude and azimuth values in the TVAZ need be entered. Thanks to this the TVAZ is much easier and faster to use than the TVA. A relative shortcoming of the TVAZ consists in that owing to a very slow but continuous change in star declinations and right ascensions, the star altitudes listed in the TVAZ become insufficiently accurate; because of this every 7 – 8 years the TVAZ has to be revised and republished.

Example 7. Sidereal time $S = 191°$; latitude of fix $\varphi = 48°$. Find from TVAZ the altitude and navigational azimuth of the star Regulus.

From table 4 we find the altitude of Regulus $H = 41°24'$; navigational azimuth of Regulus $A = 236°$.

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Table 3

PART OF AN EVEN-NUMBERED PAGE FROM TVA-2

+15°

φ / t	46° h	46° f	46° A	48° h	48° f	48° A	50° h	50° f	50° A	52° h	52° f	52° A
0°	59°00′	10	180°	57°00′	10	180°	55°00′	10	180°	53°00′	10	180°
2	58 57	10	176	56 58	10	176	54 58	10	177	52 58	10	177
4	58 49	10	173	56 50	10	173	54 51	10	173	52 52	10	174
6	58 36	10	169	56 38	10	169	54 40	10	170	52 42	10	170
8	58 17	10	165	56 21	10	166	54 24	10	167	52 27	10	167
10	57 53	10	162	55 59	10	163	54 04	10	163	52 09	10	164
12	57 24	10	158	55 33	10	159	53 40	10	160	51 47	10	161
14	56 51	10	155	55 02	10	156	53 12	10	157	51 21	10	158
16	56 13	9	151	54 27	9	153	52 40	10	154	50 52	10	155
18	55 31	9	148	53 48	9	150	52 04	9	151	50 19	10	152
20	54 45	9	145	53 06	9	147	51 25	9	148	49 43	9	149
22	53 56	9	142	52 20	9	144	50 43	9	145	49 03	9	146
24	53 03	9	139	51 31	9	141	49 57	9	142	48 21	9	144
26	52 07	9	136	50 39	9	138	49 08	9	140	47 36	9	141
28	51 08	9	134	49 44	9	135	48 17	9	137	46 48	9	139
30	50 07	8	131	48 46	9	133	47 23	9	134	45 58	9	136

f / Δδ	10	9	f / Δδ	10	9
0′	0′	0′			
1	1	1	16′	16′	14′
2	2	2	17	17	15
3	3	3	18	18	16
4	4	4	19	19	17
5	5	4	20	20	18
6	6	5	21	21	19
7	7	6	22	22	20
8	8	7	23	23	21
9	9	8	24	24	22
10	10	9	25	25	22
11	11	10	26	26	23
12	12	11	27	27	24
13	13	12	28	28	25
14	14	13	29	29	26
15	15	14	30	30	27

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PART OF AN ODD-NUMBERED PAGE FROM TVA-2

φ / t	46° h	46° f	46° A	48° h	48° f	48° A	50° h	50° f	50° A	52° h	52° f	52° A	t
90°	10°44′	7	79°	11°05′	7	80°	11°26′	8	80°	11°46′	8	81°	
92	9 22	7	78	9 46	7	78	10 10	8	79	10 33	8	79	
94	8 01	7	77	8 28	7	77	8 55	8	77	9 21	8	78	
96	6 40	7	75	7 10	7	76	7 40	8	76	8 09	8	76	
98	5 20	7	74	5 53	7	74	6 25	8	74	6 58	8	74	
100	4 00	7	72	4 36	8	73	5 11	8	73	5 47	8	73	
102	2 40	7	71	3 19	8	71	3 58	8	71	4 36	8	71	
104	1 22	7	70	2 04	8	70	2 45	8	70	3 27	8	70	
106	0 04	7	68	0 49	8	68	1 33	8	68	2 18	8	68	
108	1 13	8	113	0 25	8	113	0 22	8	67	1 09	8	67	72°
110	2 29	8	115	1 39	8	115	0 48	8	115	0 02	8	65	70
	3 44	8	116	2 51	8	116	1 58	8	116	1 05	8	116	68
	4 58	8	118	4 03	8	118	3 07	8	118	2 10	8	118	66
	6 12	8	119	5 13	8	119	4 14	8	119	3 15	8	120	64
	7 24	8	121	6 23	8	121	5 21	8	121	4 19	8	121	62
	8 35	8	122	7 31	8	122	6 26	8	123	5 22	8	123	60
	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	28 03	10	167	26 06	10	167	24 09	10	167	22 12	10	167	12
	28 20	10	169	26 22	10	169	24 24	10	169	22 26	10	170	10
	28 34	10	171	26 36	10	171	24 37	10	172	22 38	10	172	8
	28 46	10	173	26 46	10	174	24 47	10	174	22 48	10	174	6
	28 54	10	176	26 54	10	176	24 54	10	176	22 55	10	176	4
	28 56	10	178	26 58	10	178	24 59	10	178	22 59	10	178	2
	29 00	10	180	27 00	10	180	25 00	10	180	23 00	10	180	0
	h	f	A	h	f	A	h	f	A	h	f	A	t / φ
	46°			48°			50°			52°			

Δδ / f	8	7
0′	0′	0′
1	1	1
2	2	1
3	2	2
4	3	3
5	4	4
6	5	4
7	6	5
8	6	6
9	7	6
10	8	7
11	9	8
12	10	8
13	10	9
14	11	10
15	12	10
16	13	11
17	14	12
18	14	13
19	15	13
20	16	14
21	17	15
22	18	15
23	18	16
24	19	17
25	20	18
26	21	18
27	22	19
28	22	20
29	23	20
30	24	21

Example 8. Sidereal time S = 183°. Determine with the help of the TVAZ the latitude of fix, if the measurement of the altitude of Polaris from latitude is not needed.

Using table 4, we find that the latitude of fix is $\varphi = 47°57' + 53' = 48°50'$.*

Table 4

S from 180° to 225° — $\varphi = 48°$

S	Correction for the Altitude of the Polar Star	Vega *h*	Vega *A*	Arcturus *h*	Arcturus *A*	Spica *h*	Spica *A*	Regulus *h*	Regulus *A*
180°	+52′	22°39′	57°	50°45′	125°	28°19′	157°	47°01′	223°
181	+52	23 12	57	51 18	126	28 34	158	46 33	225
182	+53	23 46	58	51 50	128	28 49	159	46 05	226
183	+53	24 20	58	52 22	129	29 03	160	45 36	227
184	+54	24 55	59	52 53	130	29 16	161	45 06	228
185	+54	25 29	60	53 23	132	29 29	162	44 35	230
186	+54	26 04	60	53 53	133	29 41	164	44 04	231
187	+55	26 39	61	54 22	134	29 52	165	43 33	232
188	+55	27 14	61	54 50	136	30 02	166	43 02	233
189	+55	27 49	62	55 18	137	30 12	167	42 30	234
190	+56	28 25	62	55 45	138	30 21	168	41 57	235
191	+56	29 00	63	56 12	140	30 29	169	41 24	236
192	+56	29 36	64	56 37	142	30 36	170	40 50	237
193	+56	30 12	64	57 02	143	30 43	172	40 16	238
194	+57	30 49	65	57 26	145	30 48	173	39 42	239
195	+57	31 25	65	57 48	146	30 53	174	39 07	240
196	+57	32 02	66	58 10	148	30 57	175	38 32	241
197	+57	32 38	66	58 31	150	31 01	176	37 56	242
198	+58	33 15	67	58 51	151	31 03	177	37 21	243
199	+58	33 52	68	59 10	153	31 05	178	36 45	244
200	+58	34 30	68	59 28	155	31 06	179	36 09	245

9. Geographical Location of Stars and Circles of Equal Altitude

We have already said above (see Section 1) that a navigator, on having measured in flight the altitude of any star can, after processing the results of his

*For obtaining a more accurate magnitude of latitude of fix, it is necessary also to enter certain other corrections into the measured altitude of the Polar Star; see Sections 13 and 14 of this book.

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measurements, plot on the chart the astronomical line of position at one point of which there is found the airplane (at the moment of measuring the altitude). The currently applied method of plotting astronomical lines of position constitutes modification of a method worked out as early as in 1839 by a Russian naval officer, Lieutenant M.A.Akimov.* Since this method is of great significance for controlling the course by astronomical means of air navigation, it is necessary to describe the geometric concepts on which it is based.

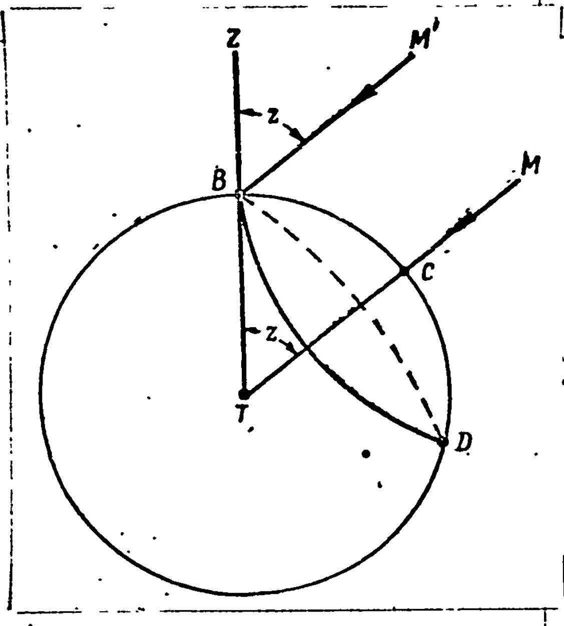

Fig.134 - Determining the Fix of an Observer from two Circles of Equal Altitude

If we mentally connect the center of the earth's sphere with any heavenly body by a straight line, this line intersects the earth's surface at a point, in which the body will be observed in its zenith. Such an assumed point is called the geographical fix of the heavenly body (abbreviated to GH of the body). In Fig.134 MC and M'B are parallel beams of a star, falling on the Earth's surface; point T is the center of the Earth, point C is the GM of the star, and point B is the location of an observer, who is obviously separated from the GM of the star by the angular distance BTC. Let us plot through point B a plumb line TZ. Then we obtain angle $\angle ZBM' = \angle BTC$, i.e., the zenith distance of the star

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*In many handbooks of maritime and air celestial navigation this method is incorrectly referred to as "Sumner's method" after Captain Sumner who proposed a much less workable version of this method at the same time as M.A.Akimov.

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equals the angular distance of the observer from the GM of the star.

Let us plot around point C on the Earth's surface a small circle BD, the spherical radius of which equals the arc CB. All points on this circle are located equidistantly from point C; consequently, the zenith distances of the star on these points will all also be equal. This small circle is termed circle of equal altitudes of a heavenly body, because, no matter what point on that circle is occupied by the observer, the zenith distance of the heavenly body, and hence also its altitude, will remain the same. It follows from the above that

$$z = \breve{CB} \text{ and } h = 90^\circ - \breve{CB}. \qquad (11)$$

No matter what is the point on the Earth's surface that is occupied by an observer, the circle of equal altitudes of any heavenly body can be always plotted through that point. In this connection, the nearer is the observer to the GM of the body the smaller will be the spherical radius of the circle of equal altitudes and, consequently, the higher will be the altitude of the body.

In order to plot a circle of equal altitudes on a terrestrial globe it is necessary to know the altitude of the heavenly body in question, and to know how to determine the geographical coordinates of the GM of the body at a given instant of time. If an observer is at point C (see Fig.134), he would see the body at its zenith and thus also at its upper culmination. But the altitude of a body situated at its zenith equals 90° and the hour angle of this star situated at its top culmination equals zero or 360°.

As a consequence of this, to an observer situated at point C (that is, at the GM of the star) eqs.(4) and (9) take on this appearance:

$$90^\circ = 90^\circ - \varphi + \delta \text{ and } 360^\circ = t_{gr} + \lambda.$$

On adopting for the latitude and longitude of the GM of the body the designations φ_* and λ_*, we obtain

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$$\varphi_* = \delta \text{ and } \lambda_* = 360^\circ - t_{gr}, \qquad (12)$$

i.e., the latitude of the GM of the heavenly body equals the declination of the body and the longitude of the GM of the body equals the complement of Greenwich hour angle to 360°. Considering that the AAE gives the declinations and Greenwich hour angles of the sun, moon and planets, and also the declination of stars, while the Greenwich hour angles of stars may be calculated from a modified eq.(3), the geographical coordinates of the GM for all these heavenly bodies may be calculated for any instant of time with the help of the AAE. Knowing these coordinates and the altitude of a heavenly body, it is possible to plot on the globe the corresponding circle of equal altitudes of the body.

Let us assume that at a certain instant of zone time T_p a navigator measured the altitudes of two stars*, which proved equal to h_1 and h_2. In order that on the basis of these measurements he could plot his fix on the globe, he must proceed as follows:

a) From eq.(7) find the corresponding instant of Greenwich time T_{gr}.

b) On using the AAE, find for the instant of T_{gr} the declinations and Greenwich hour angles of the two stars;

c) From eq.(12) calculate the latitude and longitude of the geographical fixes of both stars, φ_{*1}, λ_{*1}, and φ_{*2}, λ_{*2};

d) Use the obtained values of the longitude and latitude to plot on the globe the geographical fixes of stars C_1 and C_2 (Fig.135).

e) Calculate the zenith distance of the stars by the formulas $z_1 = 90^\circ - h_1$, and $z_2 = 90^\circ - h_2$;

f) Plot on the globe (with dividers) around the points C_1 and C_2 two circles

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*If the altitudes are not simultaneously measured, one of them must be corrected for the path traveled by the airplane (see Section 13).

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of equal altitudes with spherical radii equal to z_1 and z_2.

The two circles of equal altitude plotted by such a method on the globe intersect not at one point but at two. Therefore the navigator must decide, which of these two points indicates his fix, which is easily done, since usually the points of intersection of the circles of equal altitudes are separated from each other by a distance of several thousand kilometers.

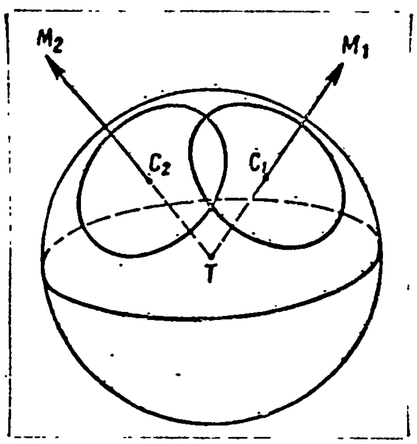

Fig.135 – Method of Plotting Straight Equal Altitudes on the Chart

Thus the problem of determining the fix of an observer with the help of two circles of equal altitudes is solved very simply and wholly definitely but the resulting accuracy is not great. This occurs mainly owing to the fact that the terrestrial globe is not an accurate instrument and it is impossible to avoid considerable errors when plotting circles of equal altitudes on that globe, with dividers. In flight the use of a globe is especially inconvenient because a large globe is too cumbrous, and on a small globe it is not possible to obtain any satisfactorily accurate results owing to its reduced scale. Owing to this, globes usually are not used for drawing astronomical lines of position, but geographical charts of sufficiently large scale are used. However, in this case the calculation and the graphic part of the work grow much more complex.

10. Lines of Equal Altitudes

On knowing the measured altitude of a star, it is easy to calculate the spherical radius of its corresponding circle of equal altitude, as expressed in kilometers. It is known that one degree of a great circle arc of the terrestrial globe equals approximately 111 kilometers. Thus if we measure the altitude of a star even when very close to its zenith, for example, equal to 80°, then in this case the radius of the circle of equal altitude will be of the much greater extent of approximately 1110 km. Owing to this the arcs of circles of equal altitude, plotted on comparatively large-scale charts, are depicted by small curved lines, whose small segments can with a sufficient degree of accuracy be changed to tangential straight-line segments. These straightened segments of arcs of circles of equal altitude are called straight lines of equal altitudes (sometimes lines of equal altitudes), PRV for short.

If a navigator has measured the altitude of some heavenly body and is familiar with the approximate region in which he is located, then, by plotting on the chart a straight line of equal altitude, he is able to ascertain that he is situated at one of the points of its segment corresponding to the region of his probable locus.

Let us examine the currently universally accepted method of plotting lines of equal altitudes on charts, representing a modification of the method proposed by M.A.Akumov (see Section 8).

Let us designate by φ_p and λ_p the approximate latitude and longitude of the fix of the airplane. Let h stand for the star altitude measured at the instant T_p and corrected as necessary (see Section 13). Let us then compute for that very instant the altitude and azimuth of the star h_b and A for the point on the Earth's surface with coordinates φ_p and λ_p which we will call the computed point.

Let us assume at the beginning, that $h_b = h$, i.e., the calculated star altitude equals the measured altitude. This indicates, that at the instant of measurements the altitudes of circles of equal altitude, and hence also the straight line of equal altitude on which the airplane is situated, passed through the computed point. In this case the straight line of equal altitudes is plotted on the chart in the following manner.

As noted before, it is possible to depict straight lines of equal altitudes as tangents of the arcs of circles of equal altitudes. But tangents are always

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perpendicular to the radius of the circle, and the radius of a circle of equal altitude connects a point on the arc of the circle with its center, that is with the GM of the star. In consequence of this the direction of the radius coincides with the direction to the GM of the star and the line of equal altitudes proves to be perpendicular to this direction. But since the azimuth of the star at the computed point is known (computed), the azimuth determining the direction of the line of equal altitudes is also known; it equals A + 90° (or A – 90°) where A is the computed azimuth of the star.

Figure 136 depicts part of the Earth's surface; C is the geographical fix of a heavenly body; B is the computed point; and the dotted line NS is the meridian, passing through that point. Let us plot from this meridian in the necessary direction (that is, from point N to the East) the angle NBM, equal to the computed azimuth of the heavenly body A. Then the line BM (a great circle arc on the Earth's surface) indicating the direction to the heavenly body, must pass through point C, i.e., through the GM of the body. CB in such cases will represent the spherical radius of the circle of equal altitude of the heavenly body having its center at point C and passing through the computed point B. Now we plot through point B a straight line KL, perpendicular to the direction to the heavenly body BM.

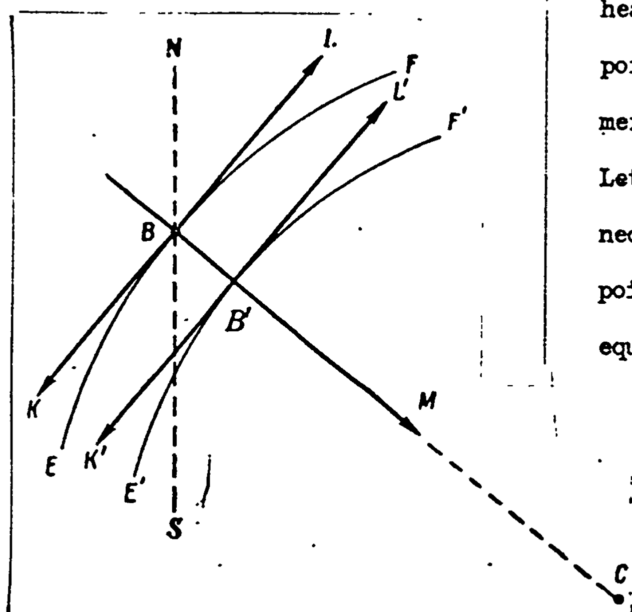

Fig.136 – Part of the Earth's Surface

This line will be the line of equal altitude of the body, since, obviously, it represents the tangent plotted from point B to the arc of the circle of equal perpendicular to the radius of the circle, and the radius of a circle of equal altitude connects a point on the arc of the circle with its center, that is with the GM of the star. In consequence of this the direction of the radius coincides with the direction to the GM of the star and the line of equal altitudes proves to be perpendicular to this direction. But since the azimuth of the star at the computed point is known (computed), the azimuth determining the direction of the line of equal altitudes is also known; it equals A + 90° (or A – 90°) where A is the computed azimuth of the star.

Figure 136 depicts part of the Earth's surface; C is the geographical fix of a heavenly body; B is the computed point; and the dotted line NS is the meridian, passing through that point. Let us plot from this meridian in the necessary direction (that is, from point N to the East) the angle NBM, equal to the computed azimuth of the heavenly body A. Then the line BM (a great circle arc on the Earth's surface) indicating the direction to the heavenly body, must pass through point C, i.e., through the GM of the body. CB in such cases will represent the spherical radius of the circle of equal altitude of the heavenly body having its center at point C and passing through the computed point B. Now we plot through point B a straight line KL, perpendicular to the direction to the heavenly body BM.

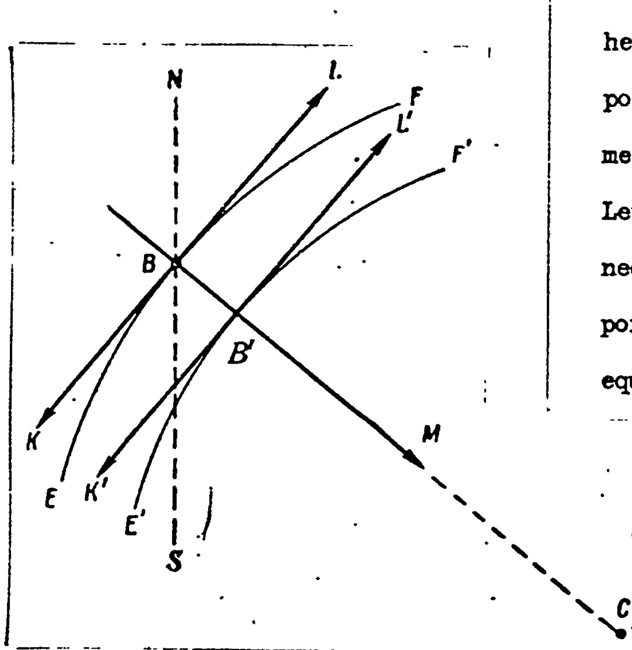

Fig.136 – Part of the Earth's Surface

This line will be the line of equal altitude of the body, since, obviously, it represents the tangent plotted from point B to the arc of the circle of equal

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altitudes EF.

Now let us assume that h_b is not equal to h, that is, the calculated altitude is not equal to the measured altitude. This indicates that the circle of equal altitude, at which the observer is situated, does not pass through computed point B. In case h is greater than h_b, that circle must be situated nearer the GM of the star than the computed point B (Fig.136 depicts the arc of such a circle, E'F'). It is obvious, the line equal altitude K'L' in this case will also prove to be displaced in the direction of GM of the star. It will be parallel to the line of equal altitudes KL, passing through the computed point, since both KL and K'L' are perpendicular to the direction of the GM of the star at BM. The distance of the line of equal altitudes K'L' from point B will be equal to the difference between the measured and the computed altitudes of the star, expressed in kilometers (assuming that 1' = 1,852 km), i.e., BB' = $\Delta h = h - h_b$. This is obvious, because BB' represents the difference of the radii of the two circles of equal altitude, of which one corresponds to altitude h_b and the other to altitude h.

If the measured altitude of the star is less than its computed altitude, the line of equal altitude would be displaced in a new direction, the reverse of the direction to the star.

The following table aids a better memorization of the rules of the displacement of the lines of equal altitude depending on the sign (plus or minus) of Δh.

Measured Altitude larger than computed altitude: $h > h_b$	Δh positive $\Delta h = h - h_b > 0$	Line of equal altitude displaced in the direction to the star
Measured altitude less than the computed altitude: $h < h_b$	Δh negative $\Delta h = h - h_b < 0$	Line of equal altitude displaced in a direction opposite the direction to the star

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Thus in order to be able to plot a line of equal altitude on a chart, it is necessary to know: the approximate coordinates of the fix of the airplane φ_p and λ_p, the azimuth of the heavenly body A and the difference between its measured and computed altitudes Δh. The two latter factors (A and Δh) are called elements of the line of equal altitudes. Their determination is the most difficult part of the work of a navigator using astronomical methods of air navigation. Examples of calculations of the elements of lines of equal altitudes and of the plotting of PRV on charts are given below in Section 14.

It is necessary to keep in mind, that the greater the length of the line of equal altitudes plotted on the chart, the greater is the error resulting from the replacement of the arc of the circle of equal altitude by the tangent to that arc. If we set the allowable value of this error at 3 km, it is possible to calculate the length of the line of equal altitudes at which this error is obtained for various values of the altitude of the star (the greater is the altitude of a star, the greater the curvature of the circle of equal altitudes).

The results of such calculations are presented in Table 5.

Table 5

Star Altitude	20°	40°	60°	70°	80°
Length of the line of equal altitudes in km. (In a side from the direction to the star.)	324	213	148	118	82

In practice the measured star altitude rarely exceeds 60°, therefore the allowable length of the line of equal altitude can usually reach 150 km.

11. The Aircraft Sextant

The Soviet-produced aircraft sextant is a goniometric instrument provided with an artificial vertical leveling attachment and an automatic integrating sight ...

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averager. Its principal purpose is to measure celestial altitudes in flight.

At the time of making measurements, the rays coming from the flashlight- or daylight-illuminated bubble level (1) (Fig.137), on being reflected in a five-sided prism (2), strike the so-called collimation lens (3), from which they exit in parallel beams. Proceeding through the principal (slightly silver plated) mirror (4), the rays strike the eye of the observer who sees the bubble of the level and at the same time the star which is reflected from the principal mirror.

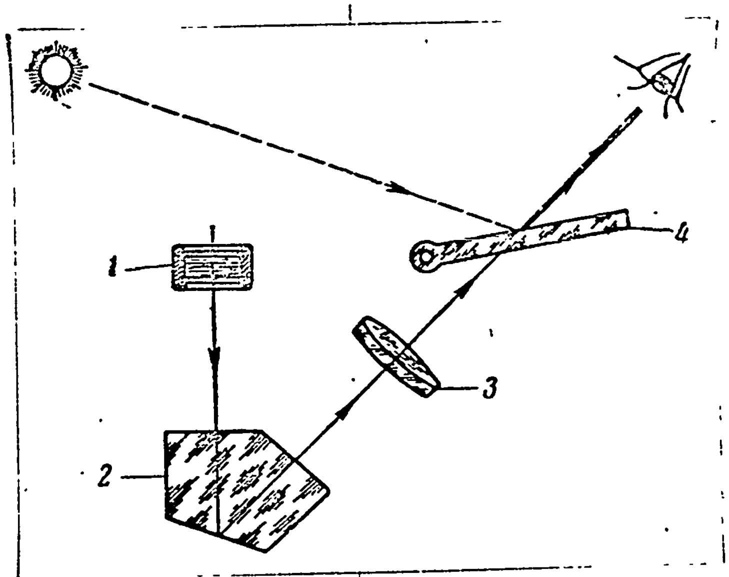

Fig.137 - Optical Diagram of Sextant

When an observer turning the knob (5) of the sextant (Fig.138) tries to obtain an approximate collimation of the star with the bubble level he links the limb of the sextant (6) with the averaging mechanism by means of a special attachment termed rocker arm (7) and tries to get the exact collimation of the star with the center of the bubble level.

Thereupon the observer presses the release lever of the timing mechanism of the sight averager (8) and in the course of all of his work he tries to keep the star in line with the center of the bubble. Upon completion of operation of the timing mechanism, the observer records the time and takes a reading of the altitude

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of the star taken down from the goniometric drum and from the scale of the sight averager. The minute scale of the averager applied against the drum rotating about the horizontal axis. Its reading is taken in the usual manner by means of a fixed index. The graduated scale of the sight averager is drawn on a disc having a vertical axis of rotation. This disc is divided into six sectors numbered in the middle 1, 2, 3, 4, and 5, respectively. Reading of degrees is made according to the number of the sector to which the fixed index will point. The ultimate value of the measured altitude is obtained as a result of compiling four calculations; calculation of tens of degrees on a small special scale, calculation of the degrees on the limb scale (in line with the arm of the rocker) and two readings of the minute and degree scales of the averager.

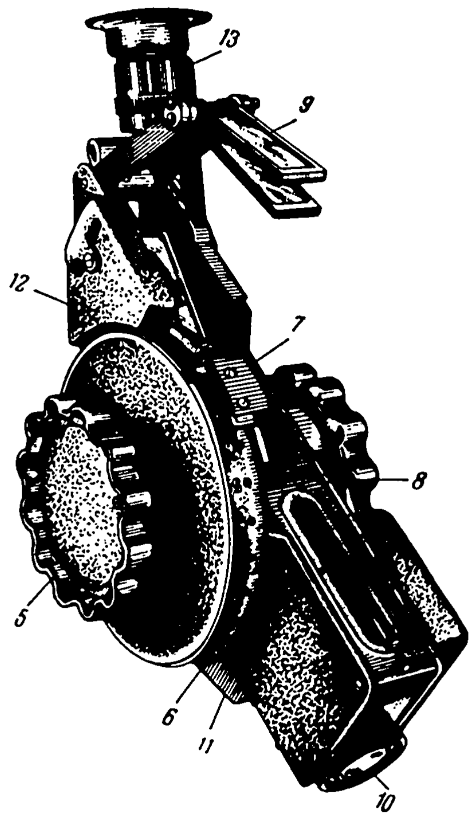

Fig.138 - Aircraft Sextant

The observer should turn special attention to the regulation of the dimensions of the bubble which is made before beginning the measurements of the star. If the bubble is very large, this reduces the accuracy of measurement (since it is more difficult to determine the center of the bubble). If, on the other hand, the bubble is excessively small, it is very slow in moving into the field of vision and, besides this, it may suddenly disappear entirely (owing to the expansion of the fluid level).

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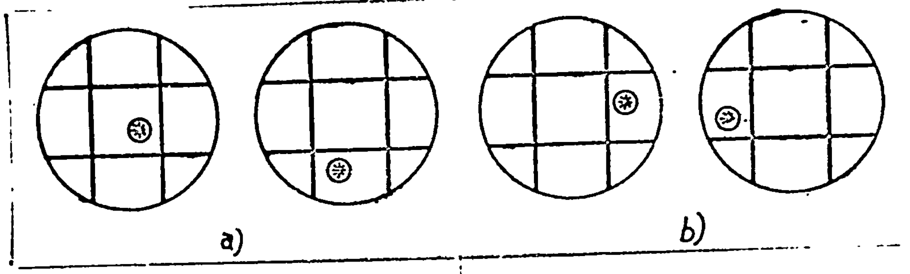
Various observers have the habit of using bubbles of various size, but most often the bubble dimensions are regulated so that its diameter equals approximately one third the side of the square which is seen in the field of vision of the sextant.



a) Correct alignment   b) Incorrect alignment

Fig.139 – Correct and Incorrect Alignments of the Bubble in the Field of Sight of a Sextant

During the conduct of sextant measurements it is possible to coincide a celestial body with the center of the bubble both inside this square and above and below it (but not to the right and not to the left of it). Figure 139 depicts two correct and two incorrect collimations of the body with the bubble in the field of vision of the sextant.

During observations of the sun, the glare of its rays is weakened by the use of moderating filters (9), and the bubble is illuminated through frosted glass (10) (see Fig.138). For illumination of bubble level during night observations the frosted glass is removed and in its place a tube with a mirror is inserted in the sextant for the purpose of reflecting the rays from a lamp placed under cover (11). The averaging scales are illuminated by another lamp which automatically switches on as soon as the timing mechanism of the averager stops working. For illuminating the scale of tens of degrees and the limb scale there is a third lamp which is switched on by pressing button (12). The lamps are driven either from the electrical system of the airplane or from a dry cell battery, enclosed in special small chamber attached to the sextant.

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[redacted]

Observation of the bubble and of the celestial body is made either by the naked eye or through the eyepiece (13) which is constituted by a half of a theatre lorgnette and provides a magnification of 2.2 times. This eyepiece has a base insertable into a socket situated on the left rear part of the sextant.

During night observations, in order not to err in the observation of a celestial body, it is advisable to observe the body first in the rays passing through the main mirror (the bubble is observed in this case in the rays reflected from the lower plane of the principal mirror) to obtain its approximate collimation with the bubble and only thereupon to begin the observation of the body through the eyepiece.

The basic virtue of the sextant lies in the possibility of using it to measure the average values of star altitudes during more or less prolonged intervals of time amounting to 40, 120 or 200 seconds, rather than measuring specific star altitudes for specific instants of time. This characteristic is not very important during ground operation of the sextant but in measurements of star altitude in flight it serves to obtain much more accurate results than are obtained with the aid of sextants having no automatic sight averagers. This happens because in flight a basic source of errors is the accelerations experienced by the airplane. No matter whether a pilot flies his airplane with or without the aid of an autopilot, the altitude, speed and direction of flight are bound to vary somewhat. Because of this the artificial vertical of the sextant, the index of which is constituted by the bubble ceases to coincide with the natural vertical and the measurement of the altitude of a star is obtained with some error. Since most of the accelerations experienced by an airplane are comparatively short-lived and do not exceed 30 – 40 seconds, then the average of the results of the measurements of the altitude of the star obtained for the period of 40 seconds proves to be more accurate than separate measurements the errors of which can reach 1° and sometimes even more.

During the measurements of star altitudes from the ground the use of the sight averaging device gives an insubstantial increase in the accuracy of the results of

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the measurements. It is necessary to remember that in those cases when the measuring is done with the averager switched off, the measurements of the altitude are derived only from the scale of ten degrees and from the limb; to these readings it is necessary to add 3^{o}. This corrects the systematic sextants error created that the readings of the scales of the averaging device would be always positive.

It is also necessary to remember that a change in the interval of continuous operation of the timing mechanism of the averager (which is achieved by turning the screw passing through the lid of the mechanism) is permissible only during the operation of the timing mechanism, since otherwise its clock lever system might be damaged.

12. The Determination of Sextant Corrections and of Accuracy of the Measurements of Star Altitudes

Any measuring device serves to obtain values of the parameters it measures with accuracy that is no better than the accuracy of its scale. However, the real accuracy of the device may prove significantly lower, since the conduct of measurements with its aid usually involves errors of distortion, some being transient and varying in both the value and the sign, and others being constant in value and therefore being termed systematic errors.

The aircraft sextant has scales serving to take readings of the measured star altitudes with an accuracy to one minute of the arc. The actual accuracy of star altitude measurement in flight is at least three times lower. The basic reasons for this are the accelerations experienced by the airplane, which we already discussed in Section 11, and also insufficiently accurate collimating of a star with the bubble during the measurements. But even if this lowered accuracy is to be reached the airplane navigator must correct the measurements of the altitude for systematic errors of an instrumental character, and also for the errors resulting from a number of reasons which are described in Section 13. In order to enter such corrections, the navigator, obviously, must know the importance of these errors, which he can learn with regard to almost all errors by studying auxiliary tables. An exception is constituted by the systematic error in the readings of the sextant itself, which the navigator must determine before the flight.

This error is the sum of two errors: the instrumental error stemming from incorrect alignment of the lubber mark on the minute scale; and the personal systematic errors of the observer, who on account of his own particular vision may not line up a celestial body with the center of the bubble but with a point situated somewhat below or above this center. The reverse value of the systematic error of sextant readings, representing the difference between the true value of the altitude of the body h and the measured altitude h_i is denoted by the letter c and is called sextant correction

$$c = h - h_i. \tag{13}$$

It is obvious, that if the correction c is added to the measured altitude h_i, then the value of the true altitude h will be obtained.

The dependence of correction c on the personal error of the observer requires that its determination be made with the help of astronomical measurements and that precisely by the navigator who will be using the sextant in flight. This correction may change with the passing of time, and therefore its determination must be repeated (at least once a month).

The simplest method of determining the error c is based on measuring the altitudes of stars near the moments of their culmination. Since at the moment of upper culmination of a star its hour angle equals zero or 360°, then on the basis of eq.(9) we will obtain:

$$t_{gr} = 360° - \lambda. \tag{14}$$

From eqs.(3) also and (10) it follows that

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$$S_{gr} = \alpha - \lambda. \qquad (15)$$

Using formulae 14 and 15 it is possible, upon solving with the help of the AAE the converse problem (see Section 6, example 3) to determine the moment of upper culmination of the sun, the moon, planets, and stars. But the altitude of any of these celestial bodies at the moment of its upper culmination can be calculated from eq.(4):

$$h = 90^\circ - \varphi + \delta.$$

The moment of lower culmination of any celestial body can be found with the help of the formulas $t_{gr} = 180^\circ - \lambda$ and $S_{gr} = 180^\circ + \alpha - \lambda$, while the altitude of the body for this moment equals $h = \varphi + \delta - 90^\circ$.

Since the altitude of a celestial body near its culmination changes very slowly, its measurement can be made for at least six minutes; three minutes before and three minutes after the calculated moment of culmination. To increase the accuracy of measuring the altitude of the body the measurements should be repeated twice or thrice during this interval of time, and averaged out. After the measured altitude will be corrected for refraction (see Section 13) the sextant correction c can be obtained from eq.(13).

Example 9. Determine the sextant correction c by measuring the altitude of the sun at the moment of its upper culmination on November 4, 1952. Geographical coordinates of the fix of the observer are: $\varphi = 56^\circ 08'$ and $\lambda = 38^\circ 12'$E. The moment of culmination is to be determined for the third time zone.

a) From eq.(14) we calculate the Greenwich hour angle of the sun

$$t_{gr} = 360^\circ - 38^\circ 12' = 321^\circ 48'$$

b) Using the AAE, we solve the converse problem and find: the Greenwich hour angle of the sun will be at the moment T_{gr} = 9 hrs. 11 min. or for the third time

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zone at the moment T_p = 12 hrs. 11 min.

c) Write down from the AAE the declination of the sun for the moment T_{gr} = 9 hrs.

$$\delta = -15^\circ 24'$$

d) From eq.(4) we calculate the altitude of the sun at the moment of its upper culmination:

$$h = 90^\circ - 56^\circ 08' - 15^\circ 24' = 18^\circ 28'$$

e) We measure the altitude of the sun near its moment of culmination with the aid of the sextant. It proves to be equal to $18^\circ 35'$.

f) We correct the measured altitude for refraction (see Section 13), and obtain

$$h_i = 18^\circ 35' - 3' = 18^\circ 32'$$

g) From eq.(13) we calculate the sextant correction

$$c = 18^\circ 28' - 18^\circ 32' = -4'$$

In another method sextant correction is determined by plotting one or several lines of equal altitude (PRV) on the chart and measuring the distance between these lines and the locus of the observer.

If the sextant correction was equal to zero, the altitude of a star measured with the help of the sextant would differ from the true altitude only by the value of the random error of measurement. In this case the PRV plotted on the chart would almost exactly pass through the locus of the observer. At a positive sextant correction the measured altitude of the star should, obviously, be obtained below the true altitude, so that the PRV will prove to be displaced relative to the locus of the observer in the direction opposite the direction to the star. In case the sextant correction is negative, the measured altitude will exceed the true one and the PRV will prove to be displaced in the direction to the star. Thus by the direction of displacement of the PRV it is possible to judge the sign of sextant correction, and the value of this correction could be compared to the arithmetic

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mean of the distances between the locus of the observer and the PRV, expressed in minutes of arc (1' = 1,852 km). This is ullustrated by the following example.

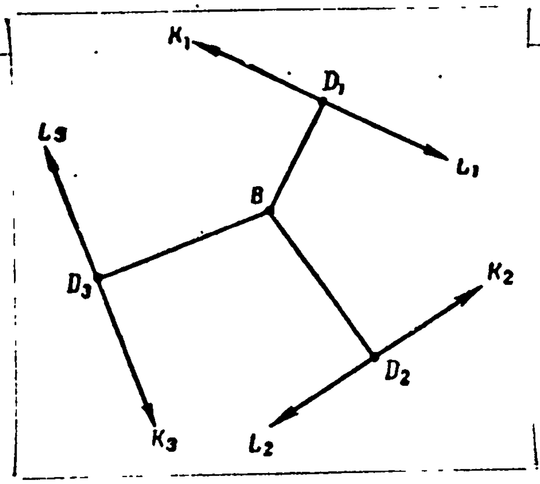

Fig.140 – Determination of Sextant Error

Let an observer be located at point B (Fig.140) and let lines K_1L_1, K_2L_2 and K_3L_3 be three PRV's. Assume that each of these PRV's proves to be displaced relative to point B in the direction toward the corresponding star, i.e., that in all three cases the measured star altitudes proved to be higher than true altitudes. This, obviously, indicates that the sextant gives an exaggerated value of altitude, i.e., its correction must be negative.

For determining the value of correction it is necessary to measure the distance from point B to each of the three PRV's. Let BD_1 = 8 km., BD_2 = 12 km and BD_3 = 13 km. Since the arithmetic mean of these distances equals $\frac{8 + 12 + 13}{3} = 11$ km, which in units of arc gives approximately 6', then the sextant correction obtained equals c = -6'.

Every navigator should be able to determine the accuracy with which he himself or one of his subordinates measures star altitudes on ground or in flight. In other words, he should be able to determine the mean value of random errors obtained during measurements of star altitudes. This is usually done on the basis of 8 – 10 measurements of the altitude of a star situated not especially close to the moment of its culmination (at least at a distance of one hour).

The order of calculation of the mean value of random errors in measuring star altitudes in flight is shown in the following example.

Example 10. At the time of a flight executed at a stable flight mode, the navigator performed eight measurements of a star at noted instants of measurement with an accuracy to 1 minute (columns 1 and 2 in Table 6). Find the mean value of random error in measuring the altitude of the star.

Table 6

T_p	h_i	7hrs 53min − T_p	Correction	Related Altitude	Error
$7^{hr}46{,}2^{min}$	11°48′	$+6{,}8^{min}$	+48′	12°36′	0′
48,2	12 04	+4,8	+34	12 38	2
49,7	12 12	+3,3	+23	12 35	1
51,4	12 22	+1,6	+12	12 34	2
53,5	12 36	—0,5	— 4	12 32	4
55,2	12 49	—2,2	—16	12 33	3
57,2	13 07	—4,2	—31	12 36	0
59,1	13 22	—6,1	—43	12 39	3
7hrs 53 min	Arithmetic mean			12°36′	± 1′,9

a) We take 7 hr. 53 m. as the basic instant (it approximates the mean instant and is expressed in whole minutes) and we calculate from this the instant of measuring the altitude of the star (Column 4 in Table 6).

b) We find the arithmetic mean for the first three instants of measurement and the first three measurements of altitude; we obtain T_1 = 7 hrs. 48 m. and h_1 = = 12°01'.

We proceed analogously in relation to the last three instants and last three altitudes, and we obtain T_2 = 7 hrs. 57.2 m. and h_2 = 13°06'.

c) We calculate the per-minute variation in the altitude of the star Δh (that is the variation of the star altitude for one minute); for this we use the formula

$$\Delta_h = \frac{h_2 - h_1}{T_2 - T_1} = \frac{13°06' - 12°01'}{9{,}2} = +7',1.$$

d) Multiplying Δ_h by the difference (7 hrs. 57 m. − T_p) we find by rounding to 1' the correction for the measured altitudes of the star (Column 4, Table 6).

e) Summing up these corrections with the measured star altitudes we obtain the

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altitudes reduced to the basic instant 7 hrs. 53 min. (Column 5, Table 6).

f) We calculate the arithmetic mean of the reduced altitudes of the star; it equals 12°36'.

g) We find the absolute values of the differences between 12°36' and the individual cited star altitudes (Column 6, Table 6); these differences may be considered as the random errors of the various measurements of star altitude.

h) We find the arithmetic mean of these differences, constituting the mean value of random errors in measuring the altitude of the star; it equals ±1'9 (the sign of random errors is not known).

Let us explain the pertinency of the solution cited in example 10. The measured altitudes of the star were not obtained equal, first, because the altitude of any celestial body changes with the passage of time, second because of the movement of the airplane in the meantime and third, owing to random errors in measurements of the star altitude. To overcome the first two causes, all measured star altitudes should be related to a single (basic) instant, whereupon they will differ from each other only owing to random errors committed by the observer. In order to obtain the mean value of these errors the arithmetic mean of the related altitudes is taken for the true value of the star altitude at the basic instant. The differences between this arithmetic mean and the individual values of related altitudes are assumed to be the random errors in measurements.

As can be seen from the given conditions of example 10, in order to determine the accuracy of in-flight measurements of star altitudes it is not necessary to know the region of the flight nor date of flight, nor time corrections, nor sextant corrections. If the flight is at night then it is not necessary to know what star is measured in altitude. The sole condition which must be met is the maintenance of a stable mode of flight.* (For footnote, see next page.)

It is possible to use this method also for determining the accuracy of measuring star altitudes from the ground. In this case, however it is possible to find

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the per-minute value of variation in the measurement of the altitude of the star not from the results received in measuring but by means of a calculation (since the observer does not change his position on the earth's surface). Table 7 gives the approximate standards of mean errors in altitude measurements on the basis of which it is possible to evaluate the skill of a pilot in measuring star altitudes from the ground.

Table 7

Celestial Body	Satisfactory	Good	Excellent
	Mean Value of Random Errors in Measuring		
Sun, Moon, and the Brightest Planets	Not more than. $\pm 2'$	Not more than $\pm 1'.5$	Not more than $\pm 1'$
Stars	Not more than $\pm 2'.5$	Not more than $\pm 2'$	Not more than $\pm 1'.5$

In measuring the altitude of a star in flight it is difficult to determine the scope of mean errors, which in some cases may characterize the skill of a navigator in conducting altitude measurements. It is possible, however, to assume, that during the absence of "flutter" of the airplane, the mean value of error in measuring the altitude of a star in flight should not exceed $\pm 3'$; for a good appraisal of the measurement, the appropriate limits of mean errors may be accepted at $\pm 4'$, and for a mediocre one, at $\pm 6'$.

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*The data cited in example 10 pertain to a flight occurring on September 23, 1949 in the region around Kirzhach; the celestial body is the sun, the airplane is a Li-2, and the sextant is a IAS-1.

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13. In-Flight Correction of Star Altitudes

The airplane navigator, on having measured in flight the altitude of any celestial body, must correct it for various systematic errors i.e., enter into it the appropriate corrections. We already described in Section 12 the sextant correction c, which the pilot must add to the measured altitude with its sign; we will now pass over to the examination of other corrections.

The correction for the refraction of the Earth's atmosphere r is introduced into measured star altitudes in all cases both at ground and at in-flight observation. It is caused by the bending of the light rays of heavenly bodies in the Earth's atmosphere. The value of this correction is increased with a decrease in the altitude of flight H and with a decrease in the altitude of star h. Corrections for refraction always must be computed from the measured altitude of a star. Table 8 gives the values of corrections for refraction for flight altitudes up to 15 km.

Table 8

Measured Altitude of Celestial Body \ Flight Altitude in km.	0	2	4	6	8	10	15
60°	1′	0′	0′	0′	0′	0′	0′
30	2	1	1	1	1	1	0
20	3	2	2	1	1	1	0
15	4	3	2	2	2	1	1
10	5	4	4	3	2	2	1
8	6	5	4	3	3	2	1
6	8	7	6	4	4	3	1
4	10	8	6	5	4	3	2

Corrections for displacement of the airplane E is entered into the measured star altitude in those cases when the navigator makes the fix of the airplane by plotting two astronomical lines of position on a chart. Since the measurements on the basis of which these lines were plotted were made at different times, the pilot must either parallelwise displace one of the lines on the chart in accordance with

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the track angle and ground speed of the airplane, and also in accordance with the time interval between the two measurements of star altitude or introduce a correction into one of the measured altitudes (usually the first) in order to relate it to the instant of measuring the altitude of another star. This correction may be calculated by the formula:

$$E = 0{,}009\,W\,(T_2 - T_1)\cos \text{PP}_*, \tag{16}$$

where W is ground speed in km/hour.

T_1 and T_2 – are the instants of measuring the star altitudes (the formula stems from the assumption that correction is introduced into a star altitude measured at instant T_1);

PP – track bearing of the star, i.e., the angle between the course line and the direction to the GM of the star.

It is not difficult to realize that the track bearing of the star equals the distance between the azimuth of the star and the track angle, i.e.

$$\text{PP}_* = A - \text{PU}. \tag{17}$$

In order to free the navigator in flight from superfluous calculations, the correction E is not calculated from eq.(16), but is taken by him from a special table compiled for this formula on the assumption that the time interval $T_2 - T_1$ equals three minutes (see Table 9). If in reality this time interval proved equal not to three, but two or four minutes, the tabulated value of correction would have to be increased or decreased by 1/3. The correction for E is the greater the greater is the ground speed of the airplane and the longer is the time interval $T_2 - T_1$ and also the closer the track bearing is to 0° or to 180°. At track bearings close to 90° or 270°, this correction changes to zero. If a track bearing ranges in intervals from 0° to 90° or from 270° to 360°, correction E is positive; if the track

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Table 9

CORRECTIONS E FOR DISPLACEMENT OF AIRPLANE IN MEASURED ALTITUDE

(Altitude of first star is measured for 3 minutes until the measurement of the Altitude of Second Star)

+ PP. / W km/hr	0° 360	10° 350	15° 345	20° 340	25° 335	30° 330	35° 325	40° 320	45° 315	50° 310	55° 305	60° 300	65° 295	70° 290	75° 285	80° 280	85° 275	90° 270 +
200	5′	5′	5′	5′	5′	5′	4′	4′	4′	3′	3′	3′	2′	2′	1′	1′	0′	0′
250	7	7	7	6	6	6	6	5	5	4	4	3	3	2	2	1	1	0
300	8	8	8	8	7	7	7	6	6	5	5	4	3	3	2	1	1	0
350	9	9	9	9	9	8	8	7	7	6	5	5	4	3	2	2	1	0
400	11	11	10	10	10	9	9	8	8	7	6	5	5	4	3	2	1	0
450	12	12	12	11	11	11	10	9	9	8	7	6	5	4	3	2	1	0
500	14	13	13	13	12	12	11	10	10	9	8	7	6	5	4	2	1	0
550	15	15	14	14	13	13	12	11	11	10	9	7	6	5	4	3	1	0
600	16	16	16	15	15	14	13	12	11	10	9	8	7	6	4	3	1	0
− W km/hr / PP.	180° 180	170° 190	165° 195	160° 200	155° 205	150° 210	145° 215	140° 220	135° 225	130° 230	125° 235	120° 240	115° 245	110° 250	105° 255	100° 260	95° 265	90° 270 −

At $0^\circ < PP_* < 90^\circ$ and $270^\circ < PP_* < 360^\circ$ Correction $E > 0$ and at $90^\circ < PP_* < 270^\circ$ Correction $E < 0$

bearing is between 90° and 270°, correction E is negative.

Example 11. $W = 450$ km/hour; $PP_* = 205°$, $T_2 - T_1 = 4$ minutes. Find correction E for corrected altitude of the first star.

The tabulated value of the correction equals − 11' (see Table 9) and since the time interval is not 3 but 4 minutes, then E = − 11' − 4' = − 15'.

The correction for the lunar parallax p, which is entered into measurements of the altitude of the moon, is necessary because in the AAE the equatorial coordinates of the moon are given on the assumption that the observer is at the center of the Earth. Because of this, in order for astronomical calculations to be made correctly, the altitude of the moon measured by the navigator must be related to the center of the earth. This also is the sense of the correction for the lunar parallax.

The value of correction p is the greater the lower is the altitude of the moon and it changes somewhat one day to another. Therefore it is given for each day in the AAE. The greatest value of this correction when the moon is visible at the very horizon) varies from 54' to 61'. Correction p is always added to the measured altitude of the moon.

Beside the above-described corrections, the in-flight measurements of star altitudes have also to be modified by the correction for the rotation of the Earth, which affects the position of the artificial vertical of the sextant. However, it is possible to proceed otherwise by not entering this correction into the measured star altitude and, instead, after plotting on the chart the astronomical line of position, displacing this line in a definite manner.

In Fig.141 the straight line CD depicts the course line; KL is an astronomical line of position, plotted on the chart without considering the influence of the Earth's rotation on the resulting measurement of the star altitude. Knowing the ground speed W and the latitude of locus φ, the navigator of the airplane must find from a special table the correction for the Earth's rotation as expressed in kilometers (see Table 10). On establishing a perpendicular line at one of the points on the course line (for example at the point of intersection of the course line with the astronomical line of position) the navigator must plot on this perpendicular a segment CE to the right of the direction of the airplane's travel. This segment should equal the determined correction. Thereupon a line K'L' should be plotted across the end of segment CE parallel to the astronomical line of position plotted on the chart. The airplane should be located on this new (displaced) line at the moment of measurement of the altitude of the star by the navigator.

If on the chart there were plotted not one but two astronomical lines of position, it is not necessary to displace each of these lines separately. Instead, it is possible simply to displace their point of intersection, i.e., the fix of the airplane made on the chart in a direction perpendicular to the right of the course line by the value of the correction taken from Table 10. As is seen from this table, the correction for the Earth's rotation must be the greater the greater are the ground speed and latitude of locus of the airplane.

Table 10

CORRECTION FOR EARTH'S ROTATION

(in kilometers)

Ground Speed in km/hr	Latitude of Locus												
	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°
200	3	3	3	4	4	4	5	5	5	5	5	5	5
250	3	4	4	5	5	5	6	6	6	6	6	6	7
300	4	5	5	6	6	6	7	7	7	8	8	8	8
350	5	5	6	6	7	7	8	8	9	9	9	9	9
400	6	6	7	7	8	9	9	10	10	10	10	10	11
450	6	7	8	8	9	10	10	11	11	11	12	12	12
500	7	8	8	9	10	11	11	12	12	13	13	13	13
550	7	8	9	10	11	12	12	13	14	14	14	14	14
600	8	9	10	11	12	13	13	14	15	15	16	16	16

It must be kept in mind, that if the flight is executed in the southern hemisphere then the displacement of the astronomical lines of position at the introduc-

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tion of corrections for the Earth's rotation must be plotted not to the right but to the left side of the line of flight.

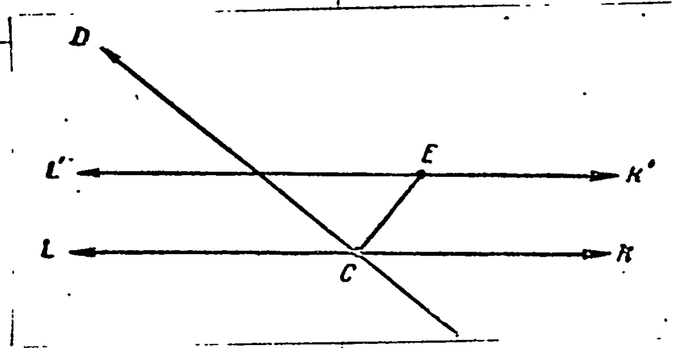

Fig.141 - Displacement of the Line of Equal Altitudes Owing to the Earth's Rotation

14. Determining the Location of Airplane in Flight with the Aid of Astronomical Measurements

If on a chart there are plotted two astronomical lines of position, the fix of the airplane is obtained at the point of their intersection. But if it is not possible to draw the second astronomical line (for example, in daytime flights, when for the most part it is possible to measure only the altitude of the sun) the locus of the airplane can be obtained at the point of intersection of the plotted astronomical position line with a reference line or with a line of position obtained with the aid of radio technical means. However, the single astronomical position line can serve both for controlling the course and for re-establishing orientation.

In Section 10 we have seen that, in order to plot on the chart a line of equal altitudes (which is the principal astronomical line of position) it is necessary to calculate its elements - the azimuth of the star A and the difference between the measured and the calculated star altitude Δh. Let us examine the two most often used diagrams for in-flight calculation of elements of lines of equal altitudes.

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The calculation of the elements of only one line of equal altitude is standard in the daytime and we shall examine it as related to the use of the TVA. The order of the calculations in this case is as follows:

a) To measure the altitude of a star the approximate longitude and latitude of the locus of the airplane φ_p and λ_p, and the sextant correction c, are recorded on a computing blank.

b) Having measured the altitude of the star, write on the blank the true (i.e., corrected for time) instant of measuring the altitude of the star T_p and the measured altitude h_b.

c) Subtracting from T_p the appropriate zone number, expressed in hours, obtain the Greenwich time instant T_{gr}.

d) Take from the AAE the declination of the star δ, its Greenwich hour angle (in whole hours for instant T_{gr}) and the correction of this hour angle for minutes and seconds of the instant T_{gr}.

e) Increase or decrease the approximate latitude λ_p in such a way that, when it is combined with the Greenwich hour angle, the local hour angle will be expressed in an even number of degrees; thereupon, calculate this local hour angle.

f) Find from the TVA the computed altitude of the star h_b and its navigational azimuth A.

g) Correct the measured altitude of celestial body h_i by entering into it the sextant correction c, the correction for refraction r (taken from a special table) and in cases when the moon is the celestial body, the correction for lunar parallax.

h) Subtract from the corrected measured altitude h the computed altitude h_B, and thus obtain the difference in these altitudes Δh, which is expressed in kilometers.

i) Plot the straight line of equal altitudes on the chart and displace it in the necessary direction by the value of the correction for the rotation of the Earth.

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Example 12. On April 30, 1952, the altitude of the sun $h_i = 49°30'$ was measured in the 3rd time zone at 14 hrs. 26 min. and 28 sec. and the approximate latitude and longitude were $\varphi_p = 50°$ and $\lambda_p = 33°$; sextant correction was $c = -4'$; flight altitude was H = 4200 m; ground speed was W = 480 km per hour; and track angle PU = 162°. Calculate the elements of the line of equal altitudes of the sun and plot it on a chart.

CALCULATION OF ELEMENTS OF THE LINE OF EQUAL ALTITUDES

30 April 1952 ; $W = 480$ km/hr ;	Sextant № 32428. $H = 4200$ m ; PU = 162°
Star	Sun
T_p $-N$	14 hrs. 26 min 28 sec. — 3 hrs.
T_{gr}	11 hrs. 26 min 28 sec
t_{gr} Correction λ_p	345°42′ 6°37′ 33°41′
t	(386° W) 26° E
φ_p δ	50° + 15° — 10′
h_i c $-r$	49°30′ — 4′ 0
h h_b	49°26′ 48°59′
Δh A	+ 27′ (+ 50 km) 220°

Displacement of PRV owing to rotation of the Earth to be charted at 10 km in the direction Aq = 252°

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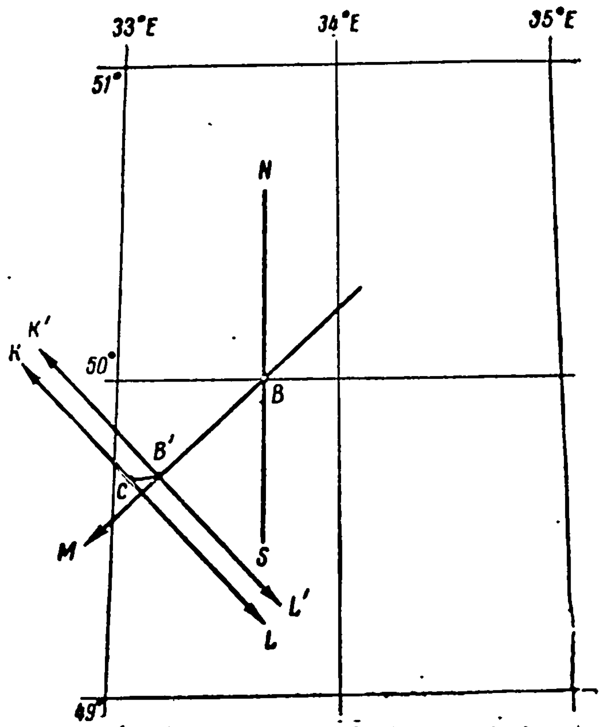
The plotting of the line of equal altitude on the chart is illustrated in Fig.142.

Calculation of the elements of two lines of equal altitudes is standard at



BB'=50km; KL-PRB, displacement due to rotation of earth (B'C=10km).

Fig.142 - Plotting a Line of Equal Altitude for the Sun

(for example No.12)

night flights. The order of making this calculation is as follows:

a) Prior to the measurement of the altitudes of two celestial bodies, write down on a blank the approximate longitude and latitude of the airplane's locus, φ_p and λ'_p, and also the sextant correction c.

b) Having measured the altitude of the first star, write on the blank the true (i.e., corrected for time) instant of measuring the star altitude T_p, and the measured altitude h_i; do the same thing in the case of the second star.

c) Deduct from the instant T_p the appropriate zone number, expressed in hours, and obtain instant Greenwich time T_{gr}.

d) Write down from the AAE the Greenwich sidereal time S_{gr} (for instants T_{gr} expressed in whole hours) and the correction of this time in minutes and seconds of the instant T_{gr}.

e) Increase or decrease the approximate longitude λ_p so that, when it is combined with the Greenwich sidereal time, we obtain the local sidereal time (for each of the stars) expressed in whole degrees; next, calculate exactly this sidereal time.

f) Find from the TVAZ the computed star altitudes h_b and their navigational azimuths A, and calculate the track bearing PP_* of the first star.

g) Correct the measured star altitude h_i, by entering the sextant correction c, correction for refraction, and (into the measured altitude of the first star only) the correction for the displacement of the airplane E.

h) Deduct the computed altitudes h_b from the corrected measured altitudes h, thus obtaining the differences in these elevations Δh, which are expressed in kilometers.

i) Plot on the chart the lines of equal altitude and displace the locus of the airplane at the point of their intersection in the necessary direction by the value of the correction for rotation of the earth.

Example 13. On March 14, 1952, in the 3rd hour zone at the instants of T_{P1} = 3 h 07 m and T_{P2} = 3 h 10 m 40 s the altitudes of two stars, Arcturus and Vega, were measured as 58°27' and 34°38', the approximate latitude and longitude at $\varphi_p = 48^\circ$ and $\lambda_p = 24^\circ$, sextant correction c = +2, altitude flight 4800 m, ground speed W = 450 km/hr, and track angle PU = 80°. Calculate the elements of the line of equal altitude and determine the position of the airplane.

Determining the position of an airplane on the chart is shown in Fig.143.

As seen from Table 4, sidereal time can also be used for measuring the altitude of still two other stars, Spica and Regulus, equal to 198° and 199°. However, measurement of the altitude of the stars Vega and Arcturus are preferable since these stars are significantly brighter than Spica and Regulus (see Table 1). But in choos-

CALCULATION OF THE ELEMENTS OF TWO LINES OF EQUAL ELEVATION

14 March 1952. W = 450 km/hr;	H = 4800 m,	Sextant № 31117. PU = 80°
Star	Arcturus	Vega
T_p $-N$	3hrs. 07 min —3hrs.	3hrs. 10 min. 40 sec —3hrs.
T_{gr}	0hrs. 07 min	0hrs 10 min 40 sec
S_{gr} Correction λ_p	171°33′ 1°45′ 24°42′	171°33′ 2°40′ 24°47′
S φ_p	198° 48°	199° 48°
h_l c $-r$ E	58°27′ +2′ 0 +5′	34°38′ +2′ —1′ —
h' h_b	58°34′ 58°51′	34°39′ 33°52′
Δh A	—17′ (—31 km) 151°	+47′ (+87 km) 68°
PP_*	71°	—
The shift in MC to allow for rotation of the earth is made made at 9 km in the direction A_q = 170°		

ing a pair of stars for observation, besides their brightness, it is necessary also to take into account the angle of intersection of their line of sight. It is known that the closer this angle is to 90° the less error is likely to occur in the exact determination of the position of the airplane, introduced in the measuring of the

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altitude of the star. Since the angle of intersection of two lines of equal altitudes obviously equals the difference of the azimuths of the corresponding stars, then in selecting the twin stars Arcturus and Vega, whose altitude was measured in Example 13, it is necessary to define successfully the relation of the angle of in-

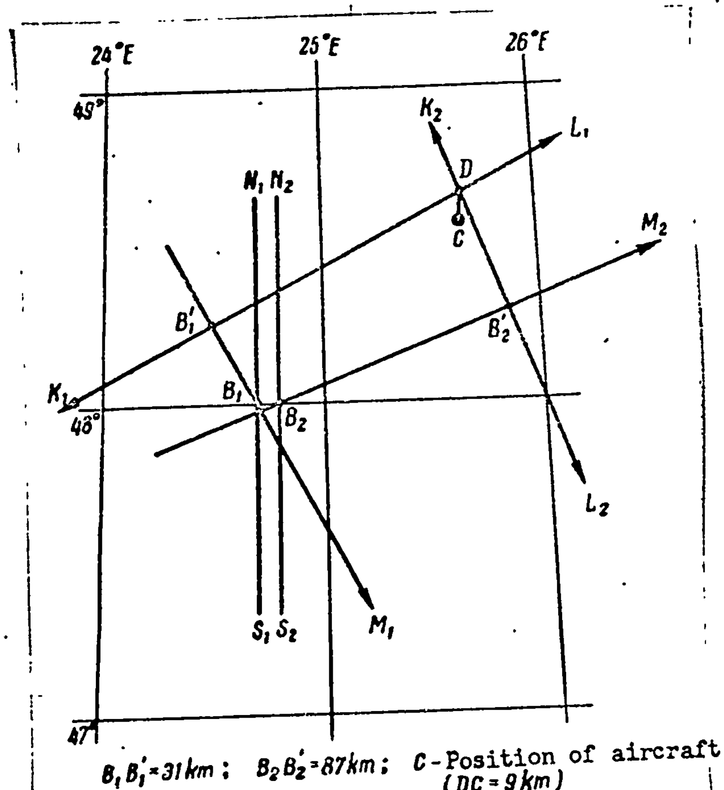

Fig.143 - Determination of the Position of the Airplane by Two Lines of Equal Altitudes (from Example 13)

tersection to their lines of equal altitude. In reality, the difference of the azimuth of these stars equals 151° - 68° = 83°, i.e., about 90°. In practice it is not acceptable to select for observation a pair of stars whose azimuth deviates from 90° (or from 270°) by more than 40°.

If the pilot, instead of measuring the altitude of Arcturus, measured the altitude of Polaris, he would be able to determine the latitude of position (see Section 7), i.e., to find the earth's parallel on which the aircraft is located at the

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moment of measuring the altitude of Polaris.

This parallel, obviously, also would be the astronomical line of position of the airplane, whose locus would be found at the point of intersection of the parallel with the straight line of equal altitude of Vega. The angle of intersection of these two lines of position of the airplane would be equal to 68^o, since the azimuth of Polaris is always equal to zero. The calculations in this case would be somewhat shorter since, for obtaining the latitude of position from the altitude of Polaris, it would be sufficient in this altitude to make only four corrections: correction of the sextant C, correction for refraction R, correction for the passage of the airplane E, and correction in the altitude of Polaris $\Delta\varphi_{pol}$ which is given in TVAZ. For example, if in example 13 at the time of 3 h 07 m, in the 3-hour zone, the measured altitude of Polaris were equal to $47^o35'$, then the latitude of the position could be computed by the following method:

h_{pol}	$47°35'$
c	$+2'$
$-r$	0
E	$+3'$
$\Delta\varphi_{pol}$	$+58'$
φ	$48°38'$

It is obvious that this calculation of the elements of the line of equal altitude is shorter than the former, that for the correction of the bearing of Polaris during passage it is possible to take an even flight angle (since the azimuth of Polaris is equal to zero), and that the sidereal time, corresponding to the moment of measuring the altitude of Polaris, need not be computed; it is possible to obtain immediately, from the sidereal time, the corresponding altitude of Vega, deducting from it 1^o.

Table 11 gives standard times of astronomical computations, recommended for the use in student flights in aircraft of the passenger type and in computation ground training.

Table 11 indicates that pilots with the greatest skill in astronomical computa-

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tions spend about 3 – 5 min in making them. In connection with this, before any flight in which celestial navigation will play an essential role, it is desirable to precompute the altitude and azimuth of stars for the purpose of shortening the time

Table 11

Astronomical Computations	Standard Time		
	Satisfactory	Good	Excellent
Computation of the elements of one PRV with the help of TVA and laying off on the chart	Not more than 7 min	From 4 to 5 min	Less than 4 min
The same with the help of TVAZ	Not more than 5 min	From 3 to 4 min	Less than 3 min
Computation of the elements of two PRV with the help of TVAZ and determination of MC	Not more than 8 min	From 5 to 6 min	Less than 5 min
Computations of the elements of one PRV and the latitude according to Polaris with the help of TVAZ and the determination of MC	Not more than 7 min	From 4 to 5 min	Less than 4 min

spent on astronomical computations during flight. Such precomputations were used on a wide scale before the transartic non-stop flights of 1936 and 1937 and also before certain other long flights and non-stop flights. At the time of World War II, special Tables of precomputed altitude and azimuths of stars were used. At present, training flights which are conducted in relatively short trips, use precomputations according to a plan suggested by Ye.Zakomore. Knowing beforehand the time of flight, the pilot chooses an itinerary with a contour of some points of known latitudes, expressed in even number of degrees, and a longitude convenient for making the computations.

For these points, which we will call means, the pilot calculates the altitude and azimuth of any star several times at intervals of 16 min as well as the corres-

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ponding elapsed time of flight. This calculation of the star altitude is supplemented by the sextant correction c (with minus sign) the correction for refraction r (with plus sign). An application of these predetermined Tables in flight is shown in the following example:

Example 14. July 16, 1952 – A pilot flying at an altitude of 4000 m at 15h 21m in the 3rd-hour zone, measured the altitude of the sun as equal to 55°58′. The pilot uses a form with the precomputed magnitude of the altitude and azimuth of the sun, computed for the mean point from the geographical coordinates $\varphi = 54°$ and $\lambda = 37°29'$ and for the subsequent time in the 3rd-hour zone: 15h 00m, 15h 16m, etc. Sextant correction is equal to −3′. To calculate the elements of lines of equal altitudes of the sun, we use the Table given below.

FORM AND COMPUTATION SCHEME

16 July 1952 Star – Sun H = 4000 m c = −3′

T_b / T	15hrs. 00min.	15hrs. 16min. / 15hrs. 21min.	15hrs. 32min.	15hrs. 48min.
$T_b - T$		−5 min		
λ_b / $(T_b - T)°$	34°29′	34°29′ / −1°15′	34°29′	34°29′
λ		33°14′		
φ	54°	54°	54°	54°
h / h_b	57°05′	55°58′ / 56°32′	55°43′	54°40′
Δh / A	190°	−34′ / 197°	203°	210°

here T_b = time, for which the altitude and azimuth of the sun have been predetermined;

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T = time of measurement of the altitude of the sun;

$T_b - T$ and $(T_b - T)^\circ$ = difference of these times, expressed in units of time and units of arc;

φ and λ_b = latitude and longitude of the mean points;

λ = longitude of computed points;

h_b = computed altitude of the sun;

A = computed azimuth of the sun;

h = measured altitude of the sun;

Δh = difference between measured and computed altitudes.

The longitude λ is obtained from the formula

$$\lambda = \lambda_b + (T_b - T)^\circ.$$

As seen from the computation scheme, the elements of lines of equal altitudes are $\Delta h = -34'$ and $A = 197^\circ$ for the computed points from the coordinates $\varphi = 54^\circ$ and $= 33^\circ 14'$.

For expediting the process of plotting PRV it is possible to use charts obtained before the flight, including the plotting of all geographic parallels in the region of the flight drawn for each 10' and also labeling of the latitude and longitude. It is also desirable to have a right-angle protractor with 10' divisions of arc of the meridian, in the scale used in flight charts (10' = 18.52 km). When laying off on the chart of PRV to reckon Δh directly in minutes of arc, without making a preliminary translation to kilometers.

15. The Astro-Compass

In regions near the magnetic poles of the earth, on passage of the aircraft over the earth's surface, the magnitude of magnetic declination shifts so extremely rapidly that the use of the magnetic compass is made exceedingly difficult. Apart from this, the horizontal components of the magnetic poles of the earth in these

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regions are of such insignificant magnitude that, in most cases, the use of the magnetic compass is generally impossible. Therefore, during flights in such regions it is most convenient to use the astro-compass with which it is possible to guide the aircraft along a predetermined course with precise accuracy; even in the immediate vicinity of the magnetic poles of the earth through interpreting the visible heavenly bodies.

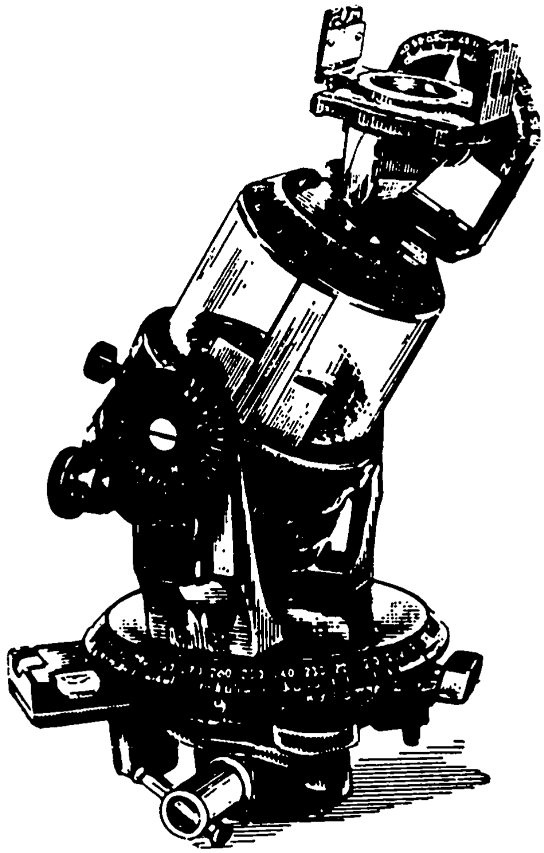

Fig.144 - Astro-Compass

As early as 1923-24 the Soviet flyer and topographer, Lubiski, for the first time in the history of air navigation worked out the idea of navigating aircraft along a course with the help of the astro-compass. These ideas were further developed by our designers, who created a solar course indicator, successfully applied during transarctic non-stop flights for over 30 years, and who are using at present the astro-compass. Such astro-compasses or celestial compasses are of simple and durable design, guaranteeing guiding of an aircraft along a course with an accuracy to within 2°, and in most cases to 1° (Fig.144). Thanks to these two sighting systems it is possible to use them for solar fixes and also for nocturnal bodies: moon, planets, and stars. With the help of a third polarized sighting system it is possible to get running fixes on the sun at twilight, when it is below the horizon, with the sky (in the required zone) free of clouds.

In order to use the astro-compass, it is necessary to know the approximate

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longitude and latitude of the airplane and to take from the AAE the inclination and the Greenwich hour angle (for the time of incipient use of the astro-compass). During observations of the sun, the lower sighting system is used and during observation of heavenly bodies at night the upper system. In both cases a dial plate sight is mounted on the scale, as demanded by the magnitude of the hour angle of the star*. The upper part of the instrument is mounted at an inclination corresponding to the latitude of position, while the longitude of position is determined on the scale by rotating the upper part of the instrument. When using the upper sighting system the inclination of the star is determined on a special scale.

For guiding the aircraft along a set course, the pilot, after having determined the fixes of all initial data on the astro-compass and having set the given course on the lower scale, banks the aircraft until the observed star is aligned, i.e., until the screen of the lower sighting assembly shows the shadow bar between the two black lines on the translucent screen (during observation of sun) or until the navigator is convinced that the star coincides with the line of sight of the upper visual sight system of the astro-compass (during observation of stars at night). After this, the pilot stops turning the plane and controls it so as to have the observed star occupy the necessary position relative to this or the other sighting systems of the astro-compass.

Since, at the time of flight, the hour angle of the star and also the latitude and longitude of position of the aircraft is continuously changing, the setting of the astro-compass must be properly corrected in time; this is done with the help of Tables prepared beforehand or from basic computations prepared at the time of flight. For this, observations of the sun are preferred since, in the lower sighting system, the hour angle is changed automatically in time, thanks to the action of

*For stars, the Greenwich hour angle is computed by transformation of eq.(3)

$$t_{gr} = S_{gr} - \alpha.$$

a time mechanism connected with this system.

For solving other basic problems with the help of the astro-compass - determining the true course of an airplane - the astro-compass is set at the latitude and longitude of position and also at the hour angle of the star, while its inclination is determined as before. At the end of setting, the pilot rotates the instrument about the vertical axis until (during observations of the sun) on the screen of the

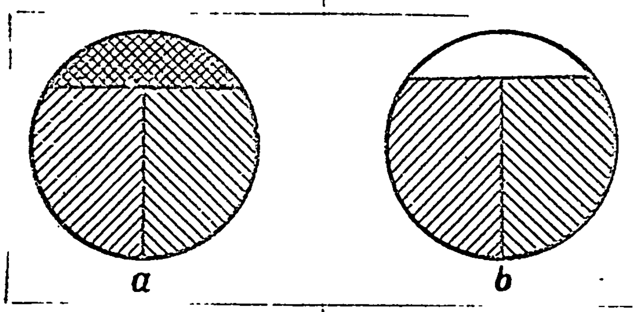

Fig.145 - Polaroids

lower sighting frame a thin line no longer appears between the reticulated screen (or during night observations) while the star is not aligned with the line of sight of the upper viewer of the sighting system. After this, the true course is read on the lower horizontal scale of the instrument.

In the navigator's work, the use in flight of the polarization of the sighting system of the astro-compass, must be checked in detail, since this comprises a series of special operations. The fixing of the hour angle of the sun and its inclination in this case is performed in the usual manner from the scale of the upper sighting system. Usually, this method is also used for determining longitude and latitude on the astro-compass. In order to avoid having to define the hour angle of the sun in flight, it is changed by 1° for four minutes; it is also recommended to fix the hour angle of the sun by the lower sighting system. In this manner, it is possible at any moment to use the scale of the lower sighting system for computing the hour angle of the sun and, in a similar manner, to change the setting of the

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hour angle on the upper sighting system.

Running fixes of the sun in this case are taken with the help of a circular polarized plate, consisting of three polaroids*. Two polaroids of identical form constitute what is called the penumbra analyzer, having equal brightness only in the case when the sun, or the bearing fix of the polaroid sighting system of the astro-compass, or the hour angle of the sun is 90° from the hour angle of the plane of bearing of the astro-compass. In order to be able to judge which of these two cases apply, a third polaroid (of smaller size) is used, having the form of segments. In case the sun is used as for taking a fix, the transparency of this polaroid is less than that of the other two (Fig.145a); in the opposite case, the transparency of the former exceeds the transparency of the latter polaroids (Fig.145b). Thus to take a fix on the sun requires either turning the airplane or rotating the astro-compass until both polaroids, constituting the penumbra analyzer, do not have the same transparency, it being known that the third polaroid (having the form of a segment) will be less transparent.

The navigator observes the transparency of the polaroids from a lateral direction, using a prism completely reflecting the inside and attached directly underneath the polarization plate. This prism can be turned in any direction which facilitates the process of observing. During examination of the polaroid through the prism, the navigator must make certain to have limited the annular field of view from the bright masses which seemingly have the same thickness in all sections. This is necessary in order that the sight lines, from the direction in which the navigator looks at the polaroid, are perpendicular to the plane of the polarization

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*A transparent plate, coated with a thin layer of a substance consisting of microscopic crystals of roughly equal shape is called a polaroid. The polaroid, to a significant degree, permits the passage of sunlight falling on it from the clear portion (blue) of the sky, depending on the arrangement of the crystals in the polaroid relative to the plate, passing across this portion, the sun, and the polaroid.

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plate (i.e., the polaroids).

If it is found that the region of the sky, illuminating the polarization plate (the center of this region is displaced with respect to the sun by 90°) is overcast but that, in the neighborhood of this region (at a distance of not more than 20°) in the direction toward the sun or in the directly opposite direction, the sky is free of clouds, a suitable increase or decrease in the deviation of the sun (not more than 20°) from these computations is required until the polarization plate shows the change to a clear part of the sky.

As shown above, by using the polarization sighting system it is possible to take fixes of the sun in twilight, when it is on the horizon. With an altitude of the sun at 0° to -7° the accuracy of bearing is within $2 - 3^{\circ}$. When the sun is below the horizon the accuracy begins to drop sharply. However, it is possible to use the polarization sighting system in cases when the sun is located below the horizon but is obscured by clouds, while clear sky appears on both sides of the circle of inclination of the sun at an angular distance of $70 - 110^{\circ}$ from the sun. In this case, an exact fix on the sun to within $2 - 3^{\circ}$ is obtained only when the altitude of the sun does not exceed 10°; for greater altitudes the accuracy of the fix is greatly reduced.

In all cases of using the astro-compass it must be understood that it is possible to secure the above-indicated accuracy of fixes on heavenly bodies only by accurate setting of the coordinates on its scale, and in the absence of any tilt of the horizontal circle of the instrument, controlled with the help of two levels.

With an astro-compass, it is also possible to define the declination of a magnetic compass and to solve certain other problems (for example, determination of the course angle of ground objects).

During short-distance flights it is possible to determine on the astro-compass the mean magnitude of the latitude and also to use (through application of the upper sighting system) the mean magnitude of the Greenwich hour angle of stars. However, by increasing the distance of flight, such averages (if the flight is not being made in the high latitudes) may lead to significant deviations of the airplane from the set course. To avoid this, at the time of flight the setting of the astro-compass coordinates is changed; for this, it is recommended to compile special Tables of latitude and longitude beforehand and to determine the time in which to change the setting. This is explained in the following example.

Example 15. April 17, 1952, aircraft flying from IPM ($\varphi_1 = 54^\circ 7'$; $\lambda_1 = 20^\circ 5'$) to KPM ($\varphi_2 = 59^\circ 2'$; $\lambda_2 = 39^\circ 8'$). Passage IPM in 6 hours in the 3rd hour zone, calculated time of flight 5 h 00 m.

Find the difference in latitude and longitude IPM and KPM $\varphi_2 - \varphi_1 = +4^\circ 5'$ and $\lambda_2 - \lambda_1 = +19^\circ 3'$.

Since the flight lasts 300 min, the change in average latitude must proceed at 1° for 66.7 min and the change in longitude at 1° for 15.5 min. Knowing this, it

Table 12

a)	b)	c)	d)
56°	$6^h 00^m$	22°	$6^h 00^m$
58	8 33	24	6 39
		26	7 10
		28	7 41
		30	8 12
		32	8 43
		34	9 14
		36	9 45
		38	10 16
		40	10 47

a) Latitude setting; b) Time of setting; c) Longitude setting; d) Time of setting

is possible to compute the time at which the latitude of position of the aircraft will equal 57° and the longitude will equal 23°, 25°, etc. At the time of flight, a setting of latitude 58° and longitude 24°, 26°, etc. must be adjusted on the

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astro-compass.

The computation of this time can be made as soon as the track is laid out, with the aid of graphs. The calculation results are given in Table 12.

Thus, the change in setting of the latitude is limited to one time while the change in setting of the longitude must be made every 31 min.

In case the actual time of completing the flight differs from the computed time or significantly differs from the time of setting the longitude and latitude, taken from the tabulation, proper corrections must be applied.

The setting of the Greenwich hour angle of the sun in the example considered, must have been derived for the time of 6 h 00 m ($t_{gr} = 225^{\circ}$); after this, it is changed automatically. During night flights, when the upper sighting system is used, it is necessary to change (increase) the setting by 1° every four minutes.

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